

# **Adoption and Implementation of Digital Twin in the Construction Industry**

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## **Abstract**

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The construction industry has evolved from a period of hand-drafted drawings to Building Information Modeling (BIM). However, in current practice, disjointed single-purpose tools created to improve communication do not fully solve information management challenges leading to suboptimal building performance in the industry. Therefore, industries are embracing a new generation of interconnected, multi-functional technologies like Digital Twin to digitally transform themselves and move beyond the margin of 3D visualization capabilities of BIM to actual production, operation, and management of building facilities.

Now we can see that the leading construction industries are giving priority to implementing Digital Twin in their companies. Almost half of the major industrial companies were predicted to use Digital Twin technology by 2021, achieving a 10% enhancement in their efficiency. In 2018, the market for global Digital Twin was valued to be USD \$3.2 billion and is predicted to reach USD \$29.1 billion by 2025. One of the prominent global research and advisory firms Gartner listed Digital Twin in the top ten list of emerging technology trends in 2019. Also, the Digital Twin market is predicted to grow around ten times in 2025 reaching USD \$27.06 billion then

back in 2017 of USD \$2.26 billion by Grand View Research Forecasts. These predictions indicate that there will be milestone progress in the adoption and implementation of Digital Twins in the construction industry.

Despite its high potential, the majority of people in the construction industry are still confused about the concept of Digital Twin technology. They are not sure what Digital Twin technology is, how it is implemented, what Digital Twin tools need to be used, and what challenges and benefits they have by having a Digital Twin system. Hence to have an in-depth idea of the Digital Twin adoption and implementation in the construction industry, this research is conducted with the aim to answer the above questions.

The research is conducted with a comprehensive literature review supported by an exploratory survey and follow-up interviews. Based on the research results, we can conclude that there is still confusion about the concept of Digital Twin in the construction Industry. The construction industry has started its journey towards digitalization but still, there are lots of things that need to be done. For example, having standard and concise data or making more collaborative environments with common data platforms can help us to implement the Digital Twin in the construction industry. Also, it requires the organizational readiness to accept changes and advancements in the industry. Overall, this research shows that the construction industry is now ready for some changes, and that change can be Digital Twin.

## **Dedication**

I like to dedicate my thesis to my  
family and friends.

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## List of Abbreviations

2D .....	Two Dimensional
3D .....	Three Dimensional
4D .....	Four Dimensional
AECO .....	Architecture, Engineering, Construction & Operation
AI .....	Artificial Intelligence
ANN .....	Artificial Neural Network
AR .....	Augmented Reality
BIM .....	Building Information Modeling
BMS .....	Building Management System
CCTV .....	Closed-circuit Television
CDC .....	Construction Digital Twin
CDE .....	Common Data Environment
DT .....	Digital Twin
GN .....	Genetic Algorithm
GPS .....	Global Positioning System
HSD .....	Human Subject Division
IoA .....	Internet of Actions
IoT .....	Internet of Things
IT .....	Information Technology
LSTM .....	Long Short-Term Memory
ML .....	Machine Learning
NASA .....	National Aeronautics and Space Administration
O&M .....	Operation & Maintenance
OT .....	Operational Technology
RFID .....	Radio Frequency Identification Devices
VDC .....	Virtual Design & Construction
VR .....	Virtual Reality

## Chapter 1: Introduction

Digital Twin Technology is a newly emerging technology in the construction industry, but its concept is not new. The concept of Digital Twin (DT) came around 2002 when it was first used in the field of aerospace. Dr. Michael Grieves first introduced the Digital Twin concept at the University of Michigan and defined it as a “Digital Twin or an equivalent to a physical product” in 2003 (Opoku et al., 2021). He and John Vickers worked together at NASA using the concept of Digital Twin for the Apollo 13 mission of Moon exploration and Curiosity Rover of Mars exploration. They built two identical space shuttles and named the remaining one on earth during the mission as the “twin”. Then they used that twin shuttle for their training while preparing for the mission and when they were on the mission, they used it to know the status of the shuttle in space (Rosen et al. 2015). Dr. Michael Grieves also introduced Digital Twin as a university course on Product Lifecycle Management in 2003, which later escalated into other fields with the development of modern technologies (Boje et al.,2020). After that, we can observe the increasing trend of adopting Digital Twin in the manufacturing industry, medical and pharmaceutical industry, transportation management systems, smart cities, and construction industry (Lee et al., 2021).

Since the emergence of Digital Twin Technology, many researchers have given its definition based on their respective fields. In Technology Roadmap 2010, the first definition of Digital Twin was given by NASA as “*an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin*” (Shafto et al. 2010, Kan and Anumba, 2019, p. 2). Also, one of the most recognized and used definitions was given by Glaessgen and Stargel in 2012: “*Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.*” (Kan and Anumba, 2019, p. 2). In general, a Digital Twin is a digital representation of a physical object where the digital part mirrors the status of a physical part as like a twin which are connected (Brilakis et al. 2019).

Although we can find lots of definitions of the Digital Twin, still we do not have a generally accepted or standard definition of the Digital Twin for the construction industry (Brilakis et al.

2019). The Digital Twin is in its developing phase and different work has been done for the implementation and adoption of the Digital Twin in the construction industry. Studying the literature on Digital Twin, we can conclude that these works have been done on different scales, like the micro-scale - a building or any utilities or facilities of the building and on the macro scale - the city or a whole nation. Overall, we can see the Digital Twin has been adopted for managing, planning, predicting, and demonstrating the building/infrastructure or city assets (Lu et al. 2020). All these studies suggest that the Digital Twins concept is mainly focused on developing advanced BIM-enabled assets management systems (Giel and Issa 2015; Song et al. 2017; Son et al. 2017; Farghaly et al. 2018) or project management systems (Taylor and Bernstein 2009; Cao et al. 2016; Ma et al. 2018).

However, the application of Digital Twin in the construction industry seems to be one of the challenging tasks in today's world. Recent trends show us that the architect and engineer are using Digital Twin maximum during the design stage whereas very minimum in the closeout stage and almost zero in the maintenance stage (Lu and Brilakis 2019). The application of Digital Twin is different in each phase of project delivery. It is found that in the design phase, Digital Twin is used for redesigning existing physical objects or evaluating the performance of the designed objects. In the manufacturing phase, it is used for real-time monitoring, planning, and controlling production whilst in the service phase, it is used for maintenance, monitoring, and fault detection (Opoku et al. 2021). Also, the literature shows that the Digital Twin research field is only focused on theoretical research and needs to expand to practical research (Ozturk, 2021). It seems to be a challenging task to create the full integration of '*cognitive technologies*', and '*BIM*' platform for achieving a Digital Twin of a building for increasing '*knowledge utilization*' for effective '*decision-making*' and efficient outcomes throughout the lifecycle of a project soon (Ozturk, 2021).

It is evident that the construction industry is afraid of accepting changes. As adopting a new technology injects higher risk in a project, the construction industry is slower to adopt it. Also, factors-like implementation cost is dominant and lack of knowledge of the benefits of implementing Digital Twin makes further challenging for implementing Digital Twin in the construction industry (Barima, 2017). Hence, the significant challenge in the modernization of the construction industry is its incompetence to adopt emerging technologies compared to other

industries like the manufacturing and automotive industries (Opoku et al. 2021). Clearly, the advancement of technology alone cannot transform the construction industry. It requires the transformation of each entity of the industry. If we really want to transform, then we need to transform the whole ecosystem of the construction industry by having proper training and management (Bock and Linner 2015, Bosch-Sijtsema et al. 2021).

The main contribution of this research would be to understand the adoption and implementation of Digital Twin technology and its relationship with the built environment. Chapter 2 contributes to the body of knowledge by articulating the Digital Twin's current state of the art and identifying questions like what needs to be done for its efficient implementation in the construction industry through literature review. Chapter 3 describes the methodology and data collection for this research. Chapter 4 explains the findings of this research in different sub-headings such as Components of Digital Twin, Tools and Cloud Platforms for Digital Twin, Implementation Strategies of Digital Twin, and Benefits and Challenges of Digital Twin with an analysis of data from surveys and interviews. Chapter 5 concludes the finding of this research with a discussion on some major points.

## Chapter 2: Literature Review

### 2.1 Definitions of Digital Twins

It has been almost two decades since the Digital Twin concept came around us in 2002. Since then, many researchers are defining Digital Twins based on their fields and expertise. Now we have more than dozens of Digital Twins' definitions. Some definitions are listed below:

Table 1: List of definitions of DT

Author	Definition of Digital Twin
Glaessgen and Stargel, 2012	An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems.
Tuegel et al. 2012	A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including sub models of the electronics, the flight controls, the propulsion system, and other subsystems.
Sedhai and Echehki, 2012	Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements.
Lee et al. 2013	Coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge.
Reifsnider and Majumdar, 2013	Ultra-high fidelity physical models of the materials and structures that control the life of a vehicle.
Majumdar et al. 2013	Structural model which will include quantitative data of material level characteristics with high sensitivity.
Grieves, 2014	Virtual representation of what has been produced.
Rosen et al. 2015	Very realistic models of the process current state and its behavior in interaction with the environment in the real world.
Rios et al. 2015	Product digital counterpart of a physical product.

Bielefeldt et al. 2015	Ultra-realistic multi-physical computational models associated with each unique aircraft and combined with known flight histories.
Bazilevs et al. 2015	High- fidelity structural model that incorporates fatigue damage and presents a fairly complete digital counterpart of the actual structural system of interest.
Schluse and Rossmann, 2016	Virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services.
Canedo, 2016	Digital representation of a real-world object with focus on the object itself.
Gabor et al. 2016	The simulation of the physical object itself to predict future states of the system.
Schroeder et al., 2016	Virtual representation of a real product in the context of Cyber-Physical Systems.
Kraft, 2016	An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin.
Bajaj et al. 2016	A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled repositories.
R. Stark et al. 2017	Digital representation of a unique asset that compromises its properties, condition and behavior by means of models, information and data.
Söderberg et al. 2017	Using a digital copy of the physical system to perform real-time optimization.
El Saddik 2018	Digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds.
Zhuang et al. 2018	Virtual, dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behavior, life and performance in a timely fashion.

Qi and Tao 2018	Virtual models of physical objects are created in a digital way to simulate their behaviors in real-world environments.
Y. Xu et al. 2019	Simulates, records and improves the production process from design to retirement, including the content of virtual space, physical space and the interaction between them.
Kannan and Arunachalam 2019	Digital representation of the physical asset which can communicate, coordinate and cooperate the manufacturing process for an improved productivity and efficiency through knowledge sharing.

Among these the most accepted definition of the Digital Twin was given by [Glaessgen and Stargel](#) in 2012; “*Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.*” ([Kan and Anumba 2019, p. 2](#)). In general, researchers are defining the Digital Twin by dividing it into components like a physical object, and a digital replica, and their interactions. The physical object in the Digital Twin system can be a real object, device, machine, service, or any intangible asset and the digital replica is the digital representation of those objects or assets and the system creating interaction and collaboration between these entities is a Digital Twin system ([Jones et al. 2020](#)). The Digital Twin system while updating the information of the physical object to the digital object, enables us to maintain a high level of synchronization and precision ([Kan and Anumba 2019](#)). Also, the Digital Twin system is a self-evolutionary system, so it uses the computers and their networks to undergo dynamic modification through communication and interaction ([Tuegel et al. 2011, Lee et al. 2021](#)). It evolves by integrating currently available and commonly required data and knowledge with the real project throughout the life cycle of that project ([Boschert et al. 2018](#)).

Recently, we can see that the definitions of Digital Twins are guided by the accuracy of a digital object. Grieves himself describes the virtual twin as accurate “*from a micro-atomic level to the macro-geometrical level*” ([Jones et al. 2020, p. 12](#)). Also, the recent publications are defining the concept of Digital Twin based on data and data systems like Digital Twin as a data mapping technology or a real-time data acquisition technology, and a data-based prediction technology which can make the union between the physical product and virtual space a reality ([Liu et al., 2021](#)). “*Digital Twin can simulate the behavior of physical entities in the real environment with*

*digital virtual models by playing a role as a bridge connecting the physical model and the information model through virtual and real interactive feedback, data fusion analysis, and decision-making iteration optimization” (Zhao et al. 2021, p. 2). “It maps, records, simulates, predicts, and manages the running track of the life cycle of objects in the physical world and digital virtual space” (Yu et al. 2020, p. 1).*

## **2.2 Types of Digital Twins**

Although there is no standard categorization of a Digital Twin, they have been categorized based on how or where they are implemented. Like if they are used in construction then it's Construction Digital Twin (CDT) (Boje et al.,2020) or in smart cities then Smart Cities Digital Twins (Austin et. al. 2020, Ford and Wolf 2020) or in the supply chain then Supply Chain Digital Twin (Barykin et al.,2020) or in networking then Networking Digital Twin (Parris et al.,2020) and so on. Among these Siemens (2021) has tried to standardize the classification of a Digital Twin as Product, Production, and Performance Digital Twin. Also, in the manufacturing industry, they have categorized Digital Twins as Product, Process, and Operational Digital Twins (Liu et al.,2020). Some of the researchers have also defined the Digital Twin as strategic (i.e. customer), organizational (i.e. new processes and practices), and cognitive (i.e. how people work) Digital Twin (Zheng et al.,2021). Also, some have classified it as a product, process, and system Digital Twin (Liu et al.,2020).

Among these, the most repetitive classification of a Digital Twin is Product, Production (Process), and Performance (Operation or System) Digital Twin. Product Digital Twin can be defined as a Digital Twin used for an efficient design of a product and this helps us to analyze how a product performs under various conditions and makes an adjustment in the virtual world to get the final product as we planned. Production or Process Digital Twin is a Digital Twin that helps us to know the best way to run a process in each condition and develops a production methodology that stays efficient under a variety of conditions. Performance or Operation or System Digital Twin is a Digital Twin that analyzes operation or any system and then provides actionable insight for informed decision making.

## 2.3 Components of Digital Twins

Primarily, the Digital Twin has been categorized into three major components. They are physical objects or products, then their virtual product in the virtual space and the connection of data that connects the loop between physical and virtual products (Grieves and Vickers 2017). The physical object can be any object, machine, device, building, utility, infrastructure system or city, or even a nation. Then the virtual entity is their representation in virtual space as a model. These digital models can be further categorized as representational models and computational simulation models (Digital Twin Consortium 2020). *“A representation model is the one that only represents the states of entities or processes whereas a computational simulation model is the executable model of a process that consists of algorithms and data that input and output representational models”* (Digital Twin Consortium 2020). Then the connection between these physical products and virtual products is a system that creates the interaction and collaboration between these products (Jones et al. 2020).

The Gemini Principles explained that the Digital Twin must represent physical reality with utmost accuracy to serve the purpose of the Digital Twin system (Bolton et al. 2018). To achieve that reality, it divided the Digital Twin into three essential elements as data, model, and visualization. The first element data is focused on the quality of data on which the twin is going to be based. We need to have clean data to achieve accuracy. Then the second element is the model which should validate our assumptions with the use of the algorithms and digital representation. Then the final element is the visualization which should have the maximum quality while presenting the output.

Also, Lin et al divided the Digital Twin system into four essential elements. They are modeling or simulation, data collection, interaction and collaboration and finally providing service. The first element of the Digital Twin is the modeling or simulation of a physical object to the virtual space creating the virtual entity. The second element is collecting the data from the physical entity and converging it to the virtual entity. The third element is the interaction or collaboration of these physical and virtual entities with their connection to the data system. The fourth and final element is to provide the service through the virtual entity as a final product (Lin et al. 2021).

## 2.4 Uses of Digital Twins

While analyzing the use cases of the Digital Twins in the construction industry we can find that the application of Digital Twins is different in the different phases of the project. In the design phase, we found that the Digital Twin is used for evaluating the performance and feasibility of the designed objects or redesigning the existing physical objects. Then in the construction phase, the Digital Twin is used for real-time monitoring, cost and schedule control, site logistic management, productivity management, and so on. And in operation and life cycle management, it is used for predictive maintenance, state monitoring, fault detection, and so on (Opoku et al. 2021).

Now construction industry is using Digital Twin technology as a smart technology like “*smart building, smart cities, smart logistics, smart grids, smart mobility in production, and so on*” (Yitmen et al. 2021). Also, the different researchers are using different technology with an aim to achieve a Digital Twin in the construction industry. Lu et al. (2020) used it for “*anomaly detection and operation and maintenance (O&M) management in an HVAC system*” (Lee et al. 2021, p. 2). Pan et al. (2021) simulates worker cooperation and task execution in house construction by using BIM, IoT, and data mining techniques as a Digital Twin. Boje et al. (2020) applied Digital Twin technology for achieving smart and lean construction. Shim et al. (2019) achieved a new generation bridge maintenance system using the concept of the Digital Twin. Kaewunruen et al. (2019) used Digital Twin for a subway station project. Sepasgozar (2020) used the combination of augmented reality and Digital Twin for data communication and education. Shirowzhan et al. (2020) created a smart city information sharing platform using the Digital Twin concept on geographic information system. The Digital Twin technology can make us able to consider the what-if scenarios along with up to current representations in a smart city (Lee et al. 2021).

Also, to digitalize the existing building and infrastructure in order to achieve the Digital Twin of existing asset different researcher has used different techniques to achieve Digital Twin. Wang et al. (2019) using the framework of scan-to-BIM have shown us the ways to achieve the Digital Twin of existing objects with reverse modeling of the buildings. Kwon et al. (2020) created basic construction shapes like planes, cuboids, and cylinders by using point clouds for achieving digital representation. Valero et. al. (2012) created an algorithm that generates the models

automatically by using point cloud data and applied it to indoor planes. These various technologies have paved the pathways for using Digital Twin in existing assets too.

## **2.5 Scales of Digital Twin Deployment**

The Digital Twin technology is in its developing phase and different work has been done for the efficient application of the Digital Twin in the construction industry. Studying the literature on Digital Twin, we can conclude that these works have been done on a different scale as the building scale like a building or any utilities or facilities or group of buildings and on the city scale like the city block or city or a whole nation (Lu et al. 2020). Also, we can see the concept of Digital Twins has evolved as a comprehensive approach to managing, planning, predicting, and demonstrating building/infrastructure or city assets (Lu et al. 2020). Studies show the complexity of data management is increasing when we increase the scale of deployment of Digital Twin. So now researchers are focused on creating suitable tools of data management for implementing Digital Twin on different scale levels with an aim of interlinking these levels.

### **2.5.1 Building Scale:**

The Building Scale Digital Twin is a concept that compromises the development of the Digital Twin of a single entity i.e., a building or an asset. It is a digital representation of all assets within a building or a single civil infrastructure including the database which can also exchange and provide information in a digital space in a unified platform (Eastman et al., 2011).

Simply a building scale Digital Twin is a small-scale Digital Twin which consists of major components forming a system of the Digital Twin. For example, a smart building with Digital Twin technology can consist of sensors, data lakes, IoT systems, integrated communications networks, edge/cloud-based analytics, data visualization systems, and so on. So, building scale Digital Twin also takes all the data of building from all sources including physically visible and non-visible like different building systems and then analyzes it to give us the wholesome digital picture of the building.

### **2.5.2 City Scale:**

*“The city-scale Digital Twin is a concept that compromises a whole city’s infrastructure and consists of Digital Twins that are constructed on different scales, built for various purposes,*

*and using different approaches, that are connected, and all built on data” (Lu et al. 2020, p. 4). “The dynamic city DTs integrate their sub-DTs and intelligent functions (e.g., AI, machine learning, data analytics, etc.) to create digital models (e.g., simulation) that can learn and update from multiple sources and represent and predict the current and future condition of their physical counterparts correspondingly and timely” (Lu et al. 2020, p. 4).*

In the construction industry, *“a DT of a city, for instance, would be built on a hierarchical architecture and include a network of sub-DTs (e.g., building DTs)” (Lu et al. 2020, p. 4).* While deploying the Digital Twin on a city scale, we need to achieve three major capacities: The first is that our Digital Twin should contain as many cities features as possible. The second is it should know the source of data it is receiving from and synchronize itself with the respective urban data sources. The third is to create a real-time response to the events occurring around the cities. Hence urban planners assisted by Digital Twin technology can simulate various data at the same time making the concept of a smart city to reality as seen in Singapore (Dassault Systèmes 2018, Lim et al. 2020).

## **2.6 Data Architecture of Digital Twin**

The architecture of Digital Twin data is composed of static and dynamic data. The static data are 2D/3D geometry information and associated asset attributes whereas dynamic data are real-time/live data collected from Digital Twin entities like buildings or a city block. These data are acquired and managed in a step compromising the architecture of Digital Twin data. These steps are Data Acquisition, Data Management, Data Analytics, and Data Visualization (Lu et al. 2020).

### **2.6.1 Data Acquisition:**

The data for the Digital Twin can be acquired by using different approaches. *“Geometric data can be acquired through 3D laser scanning and photogrammetry. Non-geometric data can be collected through other instruments, such as temperature sensors and pressure sensors” (Brilakis et al. 2019, p. 39).* Also, for acquiring data Internet of thing (IoT) is also widely used, which can be defined as *“a network of interconnected physical devices, like sensors, drones, 3D laser scanners, wearable and mobile devices, radio frequency identification devices (RFID), which is attached to construction resources to collect real-time data about the operational status of the*

project” (Pan and Zhang 2021, p. 6). “Any data in the Digital Twin should be tamper-proof and shared traceably among the participants” (Lee et al. 2021, p. 1).

Through the literature review, we can conclude that the “*BIM-IoT integration is increasingly beneficial in several prevalent domains, like construction operation and monitoring, health and safety management, construction logistics and management, and facility management*” (Pan and Zhang 2021, p. 7). Hence, BIM offers management platform and information delivery, while IoT provides a flow of real-time data. Accordingly, “*it can be envisioned that the synergy between IoT and BIM under 5G wireless communication will become the hot spot in future works, which can considerably promote the efficiency of the data collection, data transmission, and data processing based on cloud computing toward smart home, smart city, and smart construction industry*” (Pan and Zhang 2021, p. 8).

The technologies like radio-based technologies, tags, or manual methods can be used for acquiring data for automatic or semi-automatic BIM construction approaches. The radio frequency identification (RFID) technology can be used in existing buildings by installing the tags of RFID on targeted parts of the building and using a relevant scanner or reader. For example, Valero et al. (2012) by a using laser scanner and RFID created an algorithm that generates the models automatically by using point cloud data. These technologies have shown promising opportunities for acquiring the required data for the Digital Twin. However, the process of acquiring data using these technologies is complex and requires trained labor (Lu et al. 2020).

### **2.6.2 Data Management:**

According to Deloitte 2017, the Digital Twin concept is primarily focused on the information that will be needed throughout the life cycle of the asset and the management of that information. To increase the importance of these information’s, it should be structured in a reusable way. We can achieve that by creating a common data environment that connects and creates a collaborative environment among different systems of an organization forming a canonical structure of data. This canonical structure enables us to integrate different systems with the Digital Twin creating a standard format of data. Hence having a canonical structure for data management will integrate the Digital Twin with the organization and will not burden it with data management. It may lessen the amount of data that is required to be stored outside of our system,

also remove the requirements of managing larger data structures, and can enable an organization to use the Digital Twin with more flexibility and continuity to update the Digital Twin (Deloitte 2017).

The stakeholders of the construction industry may be discouraged from sharing data after knowing the value of their data set. But if that is the case then we cannot achieve the Digital Twin because the concept of the Digital Twin is primarily based on data sharing and exchange. Thus, it is critical for us to create an environment of data sharing and data exchange. We should be able to show our stakeholders how sharing the data can increase the value of their data set. The value of the data set can be the added value to their physical assets. Also creating an environment where all stakeholders share the data can lessen the burden on a single organization for data management (Lu and Brilakis 2019).

### **2.6.3 Data Analytics:**

Data Analytics is a major part of the data architecture of the Digital Twin. It is crucial to get the right data at right time for the sustainability of a project. For example, In Europe and Great Britain, almost 77% of rail and road projects had cost overruns above 29% of the estimated cost by engineers (Salling and Leleur 2015; Vick and Brilakis 2018). This was because of the lack of the right data at right time for the maintenance and upgrade of those projects (Ariyachandra and Brilakis 2020). So, data analytics is an important aspect of the Digital Twin, and it plays a vital role in achieving useful information from the data that we have in the Digital Twin system.

Also using the machine learning technology in Digital Twin can convert data into useful information and help us to inform the concerned bodies for taking the operational actions. For example, having a Digital Twin with Long Short-Term Memory (LSTM) recurrent neural network models and Genetic Algorithm (GN) or Artificial Neural Network (ANN) based scheduling approaches (O'Dwyer et al. 2020). These machine learning tools can help us in analyzing the data that we have to achieve useful information.

### **2.6.4 Data Visualization:**

The way we visualize the data can enhance the benefit of the Digital Twin application because a better visualization tool can increase the consistency and accuracy of the information

we received from our data. For example, using Big Data analytics can provide us with more useful information which can be used in our decision-making process. Also having a Digital Twin simulation for analyzing these data can make us more proactive than reactive in our monitoring processes. The different methods of visualization like virtual reality integration can benefit us in the advancement of our organization by visualizing our company strategies and outcome in the virtual world and informing us about our shortcomings in our strategies. This will make us able to plan and deal with what-if scenarios and hence reduces the uncertainty in our plans and methods. Also, the cloud and edge computing integration enable us to visualize data efficiently making us able to analyze a large amount of heterogeneous and semantic data (Lim et al. 2020).

## **2.7 Stakeholders of Digital Twin**

The Digital Twin technology is also developed with an aim to manage complicated relationships and systems for the stakeholders and enterprises. It is aimed to create a paradigm for interaction and collaboration of various stakeholders of the project in the virtual world too as their interaction with the physical object (Zhang et al. 2021). Lee et al. (2021) has recognized “*that for Digital Twins to serve all of society they will need to be created by a community. We must work together with a shared vision, sharing lessons alongside data*” (Lee et al. 2021, p. 3). There is immense potential of Digital Twin technology for supporting information sharing among project stakeholders like an owner, architect, engineer, contractor, and operator making them the stakeholders of Digital Twin (Lee et al. 2021).

### **2.7.1 Digital Twin Technology Vendors:**

Digital Twin Technology Vendors are the technical manpower who works on developing the Digital Twin tools and platforms for users. They are the ones who play a vital role in generating value from the Digital Twins’ technologies. They are supposed to generate that value without having a profit-oriented mindset. They should not be just marketing their products and selling the software, they should generate, organize, and make information accessible to every other stakeholder of the Digital Twin (Lu and Brilakis 2019).

### **2.7.2 Digital Twin Users:**

Digital Twin users are the building owners or the operators. They are the key decision-makers for implementing Digital Twins in a project (Lu and Brilakis 2019). They initiate the process of compiling Digital Twin in a project and then other stakeholders like the owner, designers, engineers, or contractors align their workflow with the Digital Twin System creating a data architecture of Digital Twin with a continuous flow of data throughout the lifecycle of a project.

### **2.8 Opportunities & Benefits of Digital Twin**

The most persuasive benefit that we have of the Digital Twin system is to get the right data at right time with a high level of precision and synchronization (Kan and Anumba 2019). It will enable us to reflect the physical space to the virtual space with real-time data. This will help us in the visualization process too as we can see the exact location where we have the issue. Then, this can provide us the information about the solution to that issue, enabling us to access our history records related to the issue. Also, the Digital Twin is aimed to be developed as a self-evolutionary system that allows us to have continuous updates about the project with the latest data (Tuegel et al. 2011). The self-evolution of the Digital Twin system may be achieved by using the real-time data generated in the physical space and by having the convergence and interaction between real-time data and historical data (Kan and Anumba 2019, Tao et al., 2018).

Another benefit of Digital Twin technology is it can make the environment in the construction industry more transparent and collaborative among different stakeholders like the owner, architects, engineers, contractors, operators, etc. (Kan and Anumba 2019). The Digital Twin system is composed of different sensors, gauges, measuring machines, laser scanning, and vision systems which enable it to sense and collect the real-time data of the physical asset. Hence the Digital Twin can predict the possible failures along with reacting to solve that failure. It can also feed data back to the system and act according to the stimulant information (Ozturk 2021). Also, having a Digital Twin system in an organization can increase productivity through predictive analytics and helps in mitigating the problems faced by an organization. Hence investment in Digital Twin can be beneficial for an organization as it helps us to achieve the organizational goals with mitigating the challenges an organization may face (Opoku et al. 2021).

The other opportunity that a Digital Twin provides us is to simulate “what-if” scenarios. The Digital Twin technology empowered with IoT sensors can make the BIM a living machine as it can automatically update the as-built BIM models. Thus, it can use artificial intelligence technologies in these living BIM models and find out the potential problems in advance making us able to act proactively to the problems. Then it can help us in monitoring cost overruns and schedule delays in a project too (Lee et al. 2021). Also, as modern construction organizations are having more computational power, we can see the bright future ahead to have all these opportunities provided by Digital Twins in the practical world (Angjeliu et al. 2020). The Digital Twin is also enabling us to think more innovatively. As Digital Twin can allow us for rapid ideation and prototyping of our work, we can receive feedback on our output products in advance. It will help us to update and modify our existing strategy encouraging us to have more innovative ideas (Lee et al. 2021).

## **2.9 Challenges of Digital Twin**

Although we have seen some promising changes in the construction industry, still adopting the Digital Twin is one of the challenging tasks for us. As the Digital Twin has emerged as an advanced technology for AECO organizations, implementing it solely depends on the technical ability of that organization. Also, while studying different literature, we found out that Digital Twin implementations are maximum during the design stage, some progress is in the closeout stage whereas almost absent in the maintenance stage of the project (Lu and Brilakis 2019). This may also be because of the changes that have been seen in the way we use to work in these phases. Like, in the design phase almost all work has been digitalized, whereas for the construction and close-out stage only some portion of the work has been digitized and during maintenance, we are having a gap in digitizing our work. So as Digital Twin requires full digitization of all work performed in the project, this also seems to be challenging to achieve (Lu and Brilakis 2019).

Similarly, another challenge for implementing Digital Twin is the readiness of an organization. Like, does the organization that wants to implement Digital Twin have the implementation strategy? Have they analyzed how their staff is going to work after implementing Digital Twin? Did they analyze what benefits they are going to have? Otherwise, there are higher chances that they may not achieve the benefits of the Digital Twin. So, they need to prepare the implementation strategy prior to the implementation so that their organization is ready for this

change (Love and Matthews 2019). Also, the implementation of the Digital Twin is not entirely based on technology only. There needs to be a workforce to support, and this workforce needs to have the knowledge, skills, and capability to work in a new digital work environment. So, the transformation of the construction industry to Digital Twin technology requires a transformation in the ecosystem of the construction industry which needs to be supported by training, standards, skills, and management (Bock and Linner 2015, Bosch-Sijtsema et al. 2021).

The other challenge that we may have, is a Digital Twin on itself may not achieve our expectations. The Digital Twin technologies are also in the developing phase and may not achieve the automation as we want them to, we may not be able to provide all the data required by the system to make it perform at the utmost level. Also, as the Digital Twin is an emerging technology initial investment is high at this moment and we are also not sure whether it will return our investment or not. Then there is also a question of data security as the Digital Twin is developed with the concept of data sharing and having a common data environment and yet we are not sure how we are going to provide security to our data (Peng et al., 2020). So, these are the challenge that we are still facing while implementing the Digital Twin in the construction industry.

## **Chapter 3: Methodology**

### **3.1 Research Approach**

The research on the adoption of Digital Twin Technology in the construction industry has been going on for almost more than a decade now. At the Construction Management Department of the University of Washington, Prof. Carrie Sturts Dossick and Ph.D. Student Alireza Borhani is leading the research on Digital Twin Technologies. Alireza has conducted a survey on Digital Twin Consortium in which later I got a chance to be involved. Then I did the in-depth literature analysis in Digital Twin and follow-up the survey participants by conducting interviews. This research aims to build on exploratory analysis and identify the challenges of implementing Digital Twin technology in the construction industry. Also, it will provide insights into the benefits that we can have by implementing Digital Twin technology in the construction industry.

### **3.2 Research Questions**

The concept of the Digital Twin is still new in the construction industry. As a result, there is still confusion in defining the Digital Twin in the construction industry. Not only the industry professionals but even scholars of construction have this confusion. So, with an aim to understand the concepts of a Digital Twin and find out the gaps in the construction industry, a comprehensive literature review was performed. With this literature review, I tried to explain: What is Digital Twin Technology for the construction industry?

Then while going through the literature review, I find out that the construction industry is slow to implement the new technologies. The implementation of Digital Twin seems to be very challenging, but data shows there is an increasing trend. So, to figure out the challenges of implementing Digital Twins the I tried to explore: How Digital Twin Technology is implemented in the construction industry?

Also, until now, there are no standard tools or software to implement the Digital Twin technology. Most of these technologies are in the developing phase and different companies are using different tools to achieve the Digital Twin. Hence, to understand what tools have been widely used, I tried to explore: What tools and methods (such as BIM, AR/VR, AI, 3D modeling, IoT,

Cloud Computing, etc.) have been applied in the construction industry to achieve the Digital Twin technology?

Then after knowing what and how questions, I tried to explore the implementation strategies for implementing Digital Twin Technology in the construction industry and then analyzed the benefits that we can have.

### **3.3 Methodology**

Digital Twin technology emerged as a concept in 2002 in aerospace. After that, it is slowly adopted by different industries. Now, the construction industry is also trying to implement it. Scholars and researchers of the construction industry have tried to implement Digital Twin in different ways. They are still trying to figure out the most efficient way to implement it. Different research has been carried out for implementing Digital Twin in the construction industry. There are more than 200 articles that have been published until today on the topics related to the implementation of Digital Twin in the construction industry.

Most of these research papers are focused on the implementation of Digital Twin in the construction industry. So, this research is carried out as exploratory research. It is done in three major steps. They are:

#### **3.3.1 Step 1: Literature Review**

Research started by having an in-depth literature review of Digital Twin technologies in the construction industries. The literature review was conducted by studying all the articles related to Digital Twin in the construction industry which have been published until 2021. The article was searched from different sources like ASCE library, Scopus, Web of Science, etc. Then articles were analyzed using excel sheets and categorized into Digital Twin Definitions, Types, Components, Scales, Uses, Data Architecture, Stakeholders, Opportunity & Benefits, and then Challenges.

#### **3.3.2 Step 2: Survey**

In this step of research, a survey on Digital Twin technology in the AECO industry was conducted. This survey was conducted by Ph.D. student Alireza Borhani with an aim to understand

the Digital Twin’s current state of the art, components, best practices, opportunities, and challenges of Digital Twin utilization. The survey was distributed among the industry practitioners through personal networks on LinkedIn and in collaboration with the Digital Twin Consortium (DTC) and collected 108 responses. The following table and charts show the categorization and information of respondents:

Table 2: Categorization of the Survey Respondents

Category	Definition	Percentage
DT technology developer	Technology developers/vendors that develop DT solutions and/or provide DT services	42.0%
DT technology user	Companies from any industry sectors that use DT as a technology solution	23.5%
Both DT technology user and developer	Technology developers that utilize DT solutions for their own facility/product during its lifecycle	34.6%

The research team has only contacted the professionals or industry practitioners who are active in implementing Digital Twin. The survey participants were categorized into DT technology

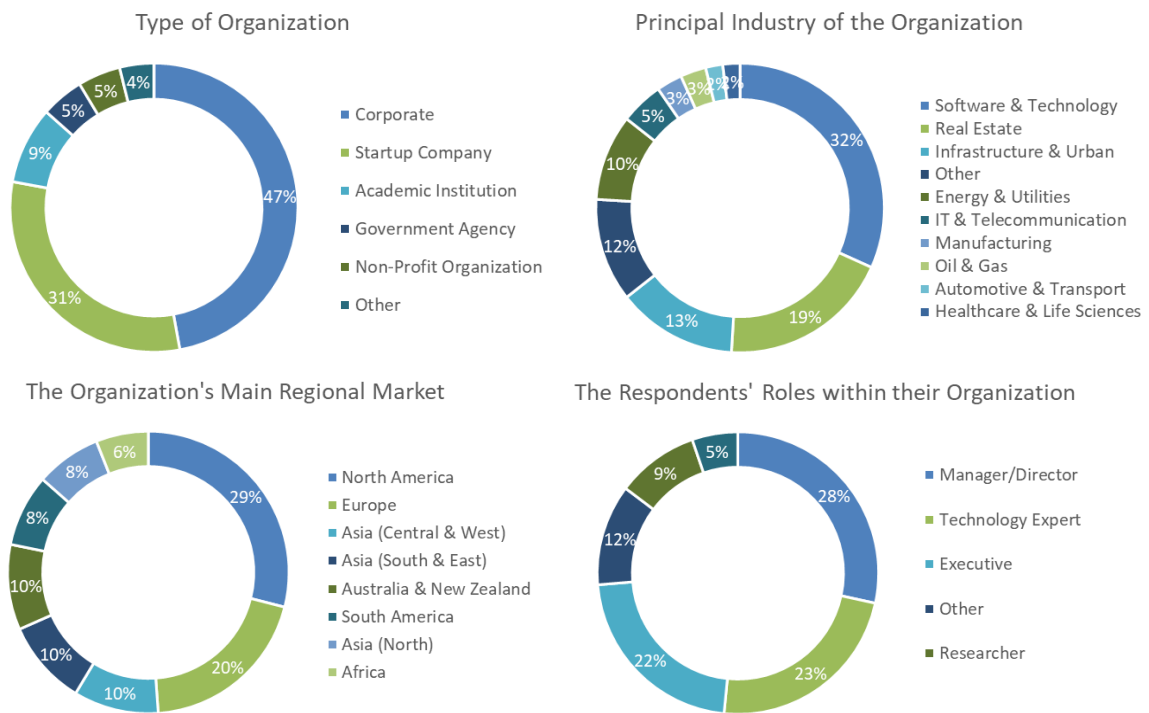


Figure 1: General Information about Survey Respondents

developers, DT technology users, and both DT technology users and developers. Then the survey was designed with different sections based on these categories. Hence, the respondents will receive a different set of questions depending on whether they are DT technology developers or users, or both. Also, an additional set of questions were created for respondents from the AECO industry to compare the Digital Twin deployment in the AECO industry to others like telecommunications or energy or utilities, and so on.

Also, about half of the survey participants reported working for corporate organizations while nearly one-third reported working in startup companies. In the AECO industry specifically, almost half of the respondents were from startups which confirms the rapid emergence of technology-based startup companies in this field. Also, more than 60% of the participants were either from the software & technology industry sector or the AECO industry (namely real estate and infrastructure & urban combined). Regarding the regional markets that participating organizations serve, about 30% of the organizations were from North America, followed by 20% from Europe, and 10% from Central/West Asia (it is assumed that some organizations especially among DT developers are active in multiple regional markets). In addition, the survey respondents were mostly managers/directors, DT technology experts (engineers, technical consultants, etc.), or executives (CEO, CTO, COO, etc.) in their organizations.

The survey was designed having three major parts: General Information, DT Technical Question, and then category-based sections like DT Users or DT for Developers, or DT for AECO Industry and others.

### **3.3.2.1 General Information**

The first part of the survey was about the background information of the respondents. The motive of this section was to collect information about the respondents. They were asked about their type of organization (like a startup, corporate, etc.), location of the organization, principal industry of their organization (like real estate, telecommunication, etc.), and their position in the organization. This part of the survey is important to know the background of the respondents and the authenticity of the data that we received.

### **3.3.2.2 Digital Twin Technical Questions**

This part of the survey was about the technical aspect of Digital Twin technology. The motive of this section was to collect information about Digital Twin technological knowledge from the respondents. They were asked to choose their organization types based on Digital Twin technology, whether they were users or developers, or both. They were also asked about the components, the benefits, and the challenges they are having in the Digital Twin implementation.

### **3.3.2.3 Category Based Section**

This part of the survey was divided as per their response as they choose them as a DT technology developer or user or both. If they choose them as a DT developer, then they were asked about the components, implementation strategy, and the methods they are using for implementing the Digital Twin technology. If they choose them as a DT user, then they were asked about tools and cloud platforms, implementation strategies (as in-house staff or consulting), and the methods they are using for implementing the Digital Twin technology.

Then the data achieved from this survey tool is further analyzed in an excel sheet. The percentage data of respondent choices in each question were further analyzed and described in chapter 4.

### **3.3.3 Step 3: Interview**

After having the data from the survey, the gaps in responses were analyzed to create an interview tool. As it was related to the human subjects, they required approval from the Human Subject Division. Then the research team sent a proposal, and the University of Washington Human Subject Division (HSD) determined that the research qualifies for exempt status. Then from survey respondents, interviewees were shortlisted, 3 from the DT Technology Developers background and 3 from the DT Technology Users background. An equal number of interviewees were shortlisted from each background in order to paint the overall picture of Digital Twin implementation in the AECO industry. The interviewees were contacted through emails and some of them through the contacts of Prof. Carrie Sturts Dossick. Then I did the interviews through zoom but due to time constraints, I ended up having a total of five interviews. The following describes the background of each interviewee selected.

## **DT Developers 1:**

DT Developers 1 is currently working for a web-services company that provides cloud services. He was in the BIM software development company for 18 years, and before that he was a practicing architect for 10 years. He has been around in the design and construction industry for almost three decades now and has been working with owners who are thinking about adopting Digital Twins. He started working in the field of Digital Twins in the early days so most of the conversation was about how to help owners/customers to implement design methodology so they would be able to get Digital Twins from Architects/Engineers. For example: If the University of Washington or Boeing or Intel or any large owner of a campus environment wants to implement Digital Twin in their project then his role was to convince them to think ahead about what information should be requested from the designing and construction team. Also, looking at what data requirements they have for their project requirements.

DT Developer 1 says, *“Digital Twin is a fairly new technology in the US as compared to Europe or Singapore or other nations. So, it really takes enlightened and envisioned customers, to think ahead for their digital requirements that they need to be asking. Mostly they are reluctant to dictate the use of Digital Twin technology as they are more concerned about the higher initial cost as opposed to the cost benefits that will come over the construction and life cycle management of the building. My role is to convince the owner how investing in Digital Twin will increase the value of the project in long run.”*

## **DT Developers 2:**

DT Developer 2 is a senior program manager for a global technology company that mainly works in the real estate and infrastructure industries. He is mostly focused on key accounts of the implementation of Digital Twins for some of their major customers in the United States of America. The implementation of Digital Twin is a multi-part task depending on how deep a customer wants to implement the Digital Twin technology. So, if we break down the Digital Twin into it two simple versions, one would be a static twin which has static asset information, 2D drawings, and 3D renders. For this case, we would be collecting documents from different construction managers and different parts of the construction phases like electrical, plumbing, mechanical, and architectural drawings. Then digitizing them and collecting those BIM models and adjusting them to our visualization platform where we can render them as 2D/3D plans. If we

are going into an in-depth Digital Twin that involves live data then we are working with different live data vendors like Building Management System, Power Monitoring System, Elevator Control System, Access Control /Security System, and things like that. Then we would be working with them to connect to their data through an open platform following the standard protocol. Then we must tag that data in open tagging format which allows us to do deeper data analysis. Next, we have to make sure we are collecting the points that we need to collect from that data system to run our version of data analytics. So, Digital Twin systems break down into the static side of things like construction documents and BIM models and the live data side of things like data integration, data tagging, data normalization, and data modeling.

DT Developer 2 says, *“People say we want a Digital Twin, but they don't realize how complex it is and think that by scanning some documents or drawings and putting them on a digital platform they can have a Digital Twin. But there are so many different degrees to having a Digital Twin. We really have to go into detail about how we are going to use this tool. Is it a single technology that we want to run our entire facilities from or an analytic tool in the back end where we still going through our traditional systems like a BMS or security systems to run our day-to-day operations? Each answer to these questions gives us different levels of Digital Twin. And I as a senior program manager helps our customers to figure out those questions.”*

### **DT Developers 3:**

DT Developer 3 is the director of the digital building lifecycle and innovation in one of the world's largest software development companies. She is an accountable director for Digital Twin technology and creates Digital Twin strategies tied to their BIM program. They want to create a BIM twin process and map all the processes and tools together which will operationalize the Digital Twin. Then people who are on the operation side will implement these strategies for operational and tactical planning. She is also accountable for how these strategies will be implemented in their portfolio.

For the past three years, they have adopted prototype Digital Twins with their partners as they themselves do not create the AEC's industry Digital Twin, but their partners do. So, they have tested different software and their capabilities and given feedback. She has also been a chair for the Digital Twin Consortium in the construction working group which is also referred to as the AEC working group. She is also preparing strategies trying to figure out what capabilities and

functionalities Digital Twins might need from the end user's perspective so that it's not limited to a single persona or a single-use case or just a single phase in the totalize cycle. So, Digital Twin is a kind of cross-pollinated in that sense but so far, they have been piloting different solutions and working them out.

#### **DT User 1:**

DT user 1 is a senior designer manager of a general contractor company who is responsible for managing BIM and VDC. She is responsible for fulfilling Digital Twin requirements that come through VDC and BIM execution plans. So, a lot of times her department oversees helping a client to define these deliverables. Also, in the last couple of years in many cases, she felt that this is where the conversation around Digital Twins started. It almost always starts and stops with the model, and she will help to find a lot of those requirements.

DT User 1 says, *“The majority of people don't even know what the word Digital Twin is. Like a bunch of people would say, we have a 3D model therefore, we have a Digital Twin. But that's not true. We can create a Digital Twin by not having a model too if we can have live data in other formats. But unfortunately, now, models are the most common solutions for having Digital Twin in a project. We as a general contractor are happy to provide you with all the information you need in different formats, but you need to be clear about what really you want. Otherwise, we are just going to do the same old things because the Digital Twin is not our tool. We are just providing parts and pieces of data to support the owner's Digital twin. They may have all the data they want but not in the format that is most digestible to them. So, tell us what format you need we are happy to do so.”*

#### **DT User 2:**

DT User 2 is a senior director of the emerging technology group of a multi-national general contractor firm. They are a national group of US branches looking ahead at what technologies are disrupting the industry and where they should focus their time to create value. They work for their own project teams and for their clients for creating operation efficiency which can potentially be through Digital Twin technology. Her role right now is in partnership with the commercial development team. They take development projects from the initial phases like investment in property or land all the way through hiring the architects to full life cycle management of a project.

She is working in conjunction with them to decide what our Digital Twin strategy will be. So, they have a definition to define. They are also doing platform research on everything that involves potentially implementing a Digital Twin.

They are looking at standards developments in implementation. Like throughout the lifecycle of a project, they have a series of BIM execution plans, state/city standards, model standards, and system standards that they are looking to implement. So, they are working on refining those standards so they can be consistent across all their projects. They need to work with different clients and each client has its own expectations. So, any client that says we want a Digital Twin as a turnover or a handover of a project then they would be looking to support them to offer that service and ensure that they are collecting the right data like the models that are representing the geometry they need for operating their building during the post-construction phase. For implementing Digital Twin, we have a beginning and an end, and we are focusing on how we get there along with implementing it in the middle of the project as well.

## Chapter 4: Findings

### 4.1 Components of Digital Twin

In general, Digital Twin has been categorized into three components: a physical entity, a virtual entity, and the connection of data between them. But when detailing these components into sub-components it has followed the path and process of dataflows like data acquisition, data management, data analytics, and data visualization. These sub-components create a practical loop of connecting the major components of Digital Twin.

The first and foremost component of Digital Twin is the physical entity or asset. This component is the major source for data acquisition. The process of acquiring data starts from the designing and planning phase of the physical asset. Then it continues through construction to the life cycle management of that asset. During this time frame data is collected by using sensors, tags (QR codes, RFID, etc.), laser scanners, CCTV, GPS, etc. All the required data like engineering, operation, and behavior data are collected from different sources throughout designing to lifecycle management of the physical assets.

Another component of Digital Twin is the virtual entity. This is the major component of the Digital Twin concept. It is the “twin” object of the physical asset consisting of all the data acquired. This component is equipped with data storage and visualization. This component helps us to convert data into information which are useful for different stakeholders of the project. It presents the collected data in a more interactive and accessible way. For example, a 3D model with the real-time data of a building that is used for maintenance.

The last component of Digital Twin is the one that connects these two physical and virtual entities which can be cloud-based system or automated systems or machine learning system which integrates the data. This component is involved throughout the process of data flow of Digital Twin. It will help us to acquire the data then manage and analyze them and finally visualize them. It is the component solely responsible for us to help in the informed decision-making process.

In the survey, the research team asked their participants to explain the Digital Twin platform or solution regarding the components of Digital Twin. The respondents could choose between four options, including, not applicable (meaning that based on the target users, the intended component is not needed), not included (meaning that the intended component may be needed but currently not provided by the tool), compatible (meaning that the intended component is not currently provided by the tool but the tool is compatible with other digital technologies that contain the component), and included (meaning that the intended component is provided by the tool). The research team got the responses as shown in the figure below:

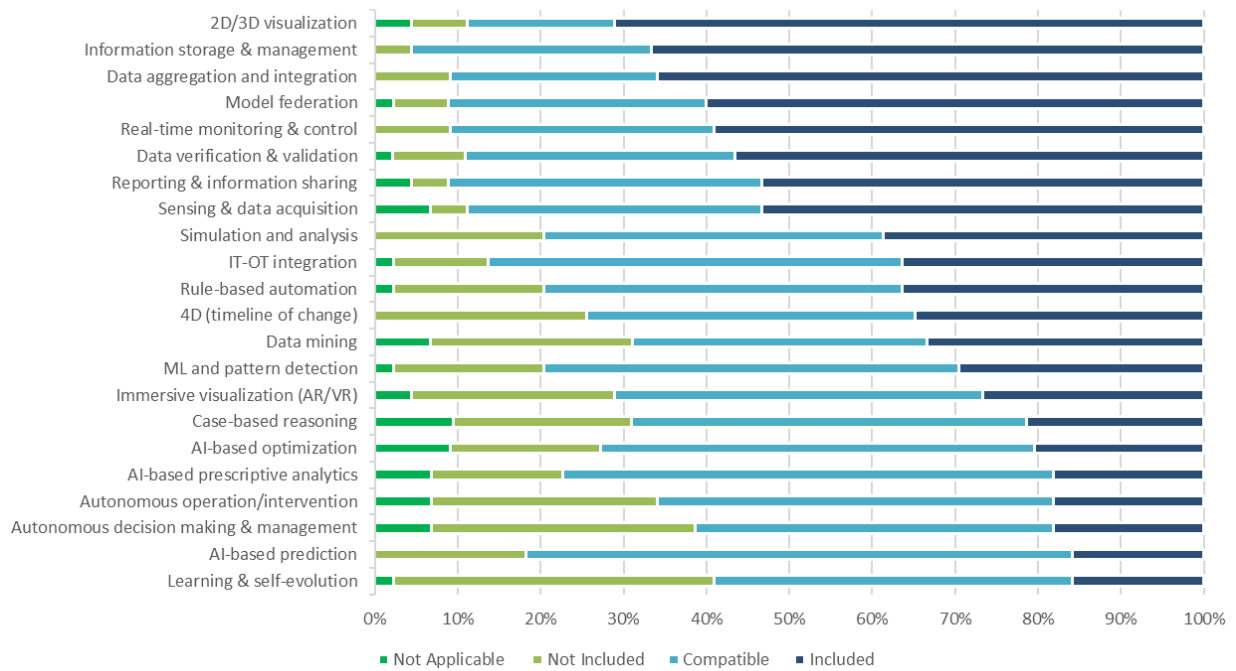


Figure 2: Components used in DT solutions

The survey result indicates that most Digital Twin solutions include the basic components of data acquisition and integration such as Information storage and management, Data aggregation and integration, as well as a model federation. The inclusion rate of data analytics components is tangibly lower and is widely dependent on the type of data analytics. The simulation-based analysis is the most conventional type of analytics while AI/ML-based predictive/prescriptive analytics are less included (about 20% of Digital Twin solutions). Regarding the data visualization, 2D/3D visualization is the most included component followed by report generation while immersive visualization (AR/VR) is significantly less included. About the Digital Twin components related to decision-making, real-time monitoring, and control, and rule-based automation are more

commonly included while few Digital Twin solutions (less than 20%) provide components like AI-based optimization and autonomous decision making.

The interview result also shows that components used for data visualization like 3D models are the most used component in the AECO industry. Most of them responded as Revit models are used for data visualization as well as data acquisition too. Also, data can be acquired and stored in simple pdf or excel format but there are problems in having the real-time data in this type of source and also, it's difficult for analyzing these data. AI/ML can be more efficient in data analytics, but they are not widely used by the AECO industry as they are still using the conventional method to analyze the data. Also, a lot of industry professionals are saying that new software for implementing Digital Twin technologies is not user-friendly and is difficult to learn.

DT Developer 1 talks about the Digital Twin components as a system that enables us to get the right information at right time. He said that these components can be any like information storage and managing systems, data acquisition systems, and 2D/3D visualization systems. He points out that the Building Information Modeling system is enabling us to create a holistic system. Although he contradicts this by saying as, like Digital Twin, BIM also has data representation and model representation. But the question is do we require data representation more than the model representation or both in the operation. The concept of the Digital Twin is more about the fact that we need both data and model representation and only having BIM we would not be able to fulfill those requirements. Also, he emphasizes that the main components of Digital Twin are governed by the data system architecture. For Digital Twin to come into existence there should be automation in the data system. Like by using sensor data or with IoT or laser scanning, machine learning through security cameras can help us to enable these components of Digital Twin.

DT Developer 2 divides the components of Digital Twin as one that will acquire the static data and the other that will acquire the dynamic or live data. He said that the components of Digital Twin that have the static data will acquire data from construction documents and BIM models and those that are from live data will acquire data from live sources and goes through the system of data architecture like data integration, data tagging, data normalization, and data modeling. Also, he emphasized that now Digital Twin has been developed as a composition of different components, but it would be easier to have a unified platform that has all these components rather than having to log in to different platforms to achieve the required data. As for data acquisition,

storage, and then visualization, there are different tools, so it is making it complex to achieve our goal. He also talks about using the existing system in construction as the component of Digital Twin. Like, Building Management System as in present Digital Twin cannot do commanding/control type of things. We are not competing so it is not required to replace BMS with Digital Twin, but we can access the BMS in the front end and verify the data that we are getting in Digital Twin and make sure the data we received is correct before we go to the data normalization.

DT Developer 3 while talking about the components of Digital Twin emphasizes data and data literacy. She said that the different methods can be used to acquire the data but at first, we should know what data we need. Also, she emphasizes that there needs to be more clarity on reality capture technology along with BIM and VDC technologies and then focusing on how people on the ground or site will be consuming these data. She said that there needs to be tighter integration of current software and hardware systems and getting the data to flow more instantaneously between people. In the present context, Digital Twin components are becoming matured in IoT, data management, etc. which is creating Digital Twin as a technology mainly focused on the management and operation of the project. But we need to be moving to other phases by creating a holistic platform.

DT User 1 describes the component of Digital Twin as the platform or system that can leverage them to achieve the data requirements of their clients as being a general contractor, they will only be delivering the products. She emphasizes that in the current industry there is still confusion about what can be the major components to create Digital Twin. She says, *“There is a hype about AR/VR and similar advanced technologies, but they are just visualization technology. If I can do that by using a simpler tool, then I need not buy those tools. But sensors can be interesting because they can provide us with much more data. But again, we should be clear on what information are we trying to get. We as a general contractor are trying to leverage data that can be used in somebody else Digital Twin as in most cases, the owner will be owning the Digital Twins.”* Also, she believes Digital Twin means linking the data but not only the digital and physical models so Digital Twin components should be a system that links the data rather than linking models.

DT User 2 describes there is much more going on in Digital Twin implementation so right now we cannot name the major components of Digital Twin. But as the Digital Twin concept explains the major components are physical object, virtual twin, and the linkage of live data between them. She said that we already have the physical and digital components, but we are still trying to figure out the components that can be used to connect these components. We as general contractors are also evaluating different components to figure out whether they are the useful components of Digital Twin or not.

While talking about the components of the Digital Twin, DT User 1 brought up the question of whether a 3D model is important as a component while implementing Digital Twin in a project or not. As the 3D model is a tool to visualize, we can visualize our data in other formats too. So, she added that lots of people say we build a 3D model, so we have a Digital Twin, but she thinks that is completely overselling their own deliverables. We cannot say having a 3D model is Digital Twin unless it will perform. Like if you have a mindset like having a model is a Digital Twin then nowadays everybody has a model and therefore everybody delivers a Digital Twin. So right now, it's hard in the AECO industry because there is a different understanding of what a Digital Twin is. But you cannot have an actual Digital Twin unless there is a linking of information for whoever needs to access that information. Also, she believes we can have a Digital Twin without having a 3D model completely. For now, even as simple as pdf is still a powerful tool to visualize some of the information. Similarly excel, some scans and photos can also help us to visualize but the main thing is how those are being linked and how those are being absorbed.

DT Developer 1 addresses that there is an ongoing question like what the value of the 3D model is. He said that we can create a database in a tabular form of all the equipment and system of the building. For example, IBM Maximo as a facility or asset management tool has been around for a long time without 3D nature. So, the question is what 3D model will get us in addition to using tools like IBM Maximo. He thinks having a 3D model will make it easier and more efficient for us in our visualization process. Like if IBM is telling us there is a work order for some equipment that needs to be fixed or changed, then the 3D model can help us to get the job done quicker by finding that piece of equipment in the 3D interface. It helps us to understand where it is, how can we reach there, and so on. But if we think in contradictory to this, in Digital Twin we can have a data from different sensors which can be acquired without twin or 3D model and if we

can achieve in that way then it's a heavy lift to maintain 3D model. So, he believes it's an emerging question in the industry about the requirements of 3D for Digital Twins.

DT Developer 2 says, *"It depends on what types of insights we are looking to gain. For example, if we are in a situation where we are unable to see physically like where the pipes are or how wide the space is then having a 3D model can be very important and useful. But if it's a simple job like related BMS, energy meters, or elevator systems then we may not require 3D. But in this case, also having a 3D model can help us to have an insight. We can also train onboarding employees by using 3D models by showing them where the pipes or other systems are in the building. So, things like that can be very handy by having a 3D model in Digital Twin systems."*

DT Developer 3 said that having a 3D model in the Digital Twin system helps us in thinking about what direction we want the built environment industry to be moving or analyzing what are the requirements and demands of end-user and are we achieving them. She added, *"It also helps us to figure out what kind of end-users or tenants we want to attract. Also, whether we are developing a sustainable smart environment or just maintaining something. Every time we make changes in the physical environment, we should be thinking about the long-term impact which can be detailed by the Digital Twin system with 3D models. So, we have so many benefits from having the 3D model in the Digital Twin system which shows its importance."*

DT User 2 also contradicts the 3D model as a component required for the Digital Twin system if we can have some other tool or ways to visualize the data. She says, *"It is certain that the 3D model plays a vital role in telling the story but for Digital Twin it is more of a data play than a model play. The 3D model does a better job for visualization but there can certainly be other ways too as we have a visualization component for the Digital Twin system. But if we are building some systems like a mechanical system that can have an impact on the whole building. Then how do we visualize that without looking at it, maybe we can use a 2D section cut or elevation or something like that but how do I totally understand the impact by using such a visualization tool? Isn't it like we are again using our conventional way and not trying to change the way we work in our industry? So, we already know 3D does a better job in visualization, so it is one of the important components of the Digital Twin system."*

Overall, there are three major components of the Digital Twin system namely the physical object and its digital replica and the connection between them. But when we try to detail the

components that are essential for Digital Twin there comes the system of data. Like what components do we have for data acquisition or management or analytics and for visualization? Also, during this research, we find out that BIM technology are playing a much more role in data visualization due to its 3D nature. Now, we are also using BIM technology along with other technology like laser scanning, different sensors, and IoT system to collect the data. Machine learning and artificial intelligence technologies have also been found to be used in the construction industry for data analytics and an advanced tool like AR/VR has also been used for visualization purposes. But these technologies are very advanced and expensive to use by simple organizations. Also, they are not that easy to learn. So, these types of technology are found to be taking time to take over the construction industry.

#### **4.2 Tools and Cloud Platforms for Digital Twin**

There are no standard tools or software for implementing Digital Twin in the AECO industry. Researchers and industry personnel are using different technologies like 3D scanning, scan-to-BIM, BIM handover, different sensor data, etc. Also, some companies are using semi-automated technologies for achieving Digital Twin. For example, LocoLab is using AI software for object recognition and creating semantic 3D models. With the help of semi-automated technologies by having minimum photographs or videos or reference measurements we can create semantic 3D models.

The other important tool for having a Digital Twin is data-sharing platforms. It is aimed to have a common data environment with standard datasets. Some commonly used data formats for sharing construction data are Industry Foundation Classes (IFC), COBie, etc. These data should have open standards which should be integrated and extended when necessary. To achieve the Digital Twin, it is important to standardize the dynamic data. Advance technology like the Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning (ML) can standardize dynamic data. Also, when extending these data, we should be able to keep personal data private and include information like how data were collected, what sensors were used, and what were the margins of data error we have.

The data of the Digital Twin should be open, decentralized, heterogenous, and interlinked. Also, these data would be shared among different participants like governments, commercial

companies, institutions, etc., which would increase the risk of data piracy. Hence, it is extremely important to have data security and there is a question among Digital Twin developers and users about how we can achieve a high level of data security. For that Blockchain technology could be an option. This would help us to increase the safety of data by decentralizing rather than having a centralized platform.

To have a boarder picture of these tools and technology, the research team asked their survey respondents a question about technologies that are more important for integration with a Digital Twin solution. The research team asked them to rank the technologies in order of importance with #1 being the most important. The importance of the listed technologies was supposed to be determined based on the value generation and return on investment for developers and users of Digital Twin.

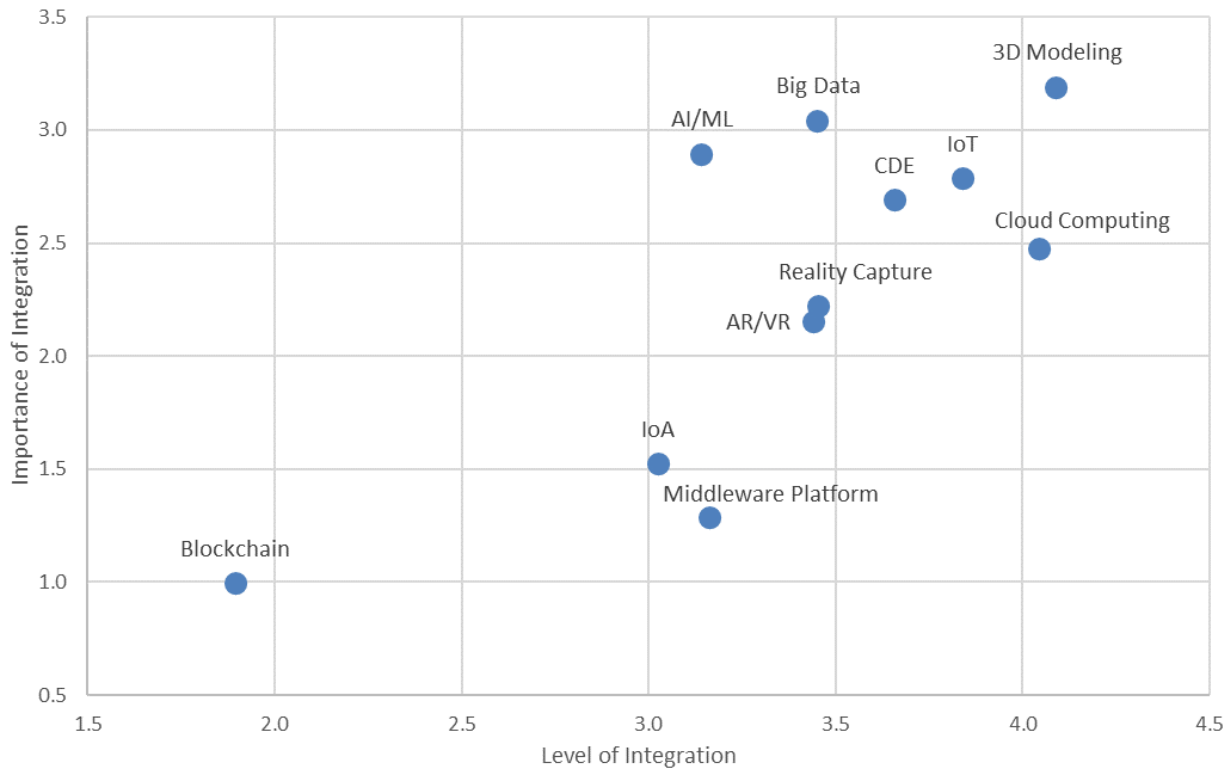


Figure 3: Importance of Integration of DT relevant Tools and Technology

As shown in the Figure 3, the top three most important tools for implementation of Digital Twin are 1. 3D modeling, which provides attributes and geometric information of the physical object, 2. big data, which enhances data transition/correlation and the feasibility of pattern detection, and 3. AI/ML utilizes analytical algorithms and supervised/unsupervised learning to

gain insight into the data. This result shows that 3D modeling is the most important tool for implementing Digital Twin in the AECO industry along with having proper data sharing, managing, and analyzing the environment.

The technologies like 3D modeling, Artificial Intelligence, Machine Learning, Cloud Computing, etc., can be achieved by using different software developed by different technology developers. There are more than dozens of software available in the market which can help in achieving Digital Twin-like Autodesk Cloud such as Tandem or Forge, Willow, Unity, etc. Also, there are different cloud platforms available for data sharing like Autodesk Cloud, Microsoft Azure, Google, etc. To know the common software that has been used by AECO users, the research team asked their survey respondents to choose the software they are using.

Most of them are using Autodesk Cloud (ACC, Tandem, Forge) as a tool for implementing Digital Twin in their industry which is followed by Willow, and Unity. Also, most of them are using Microsoft Azure as a cloud platform for Digital Twin followed by Autodesk Cloud, AWS, and Google. We find out that most of the AECO entities with Digital Twin solutions are in the urban/industry rather than in the building industry. In a survey, 55.6% of AECO industry respondents said they have existing Digital Twin solutions in their organizations.

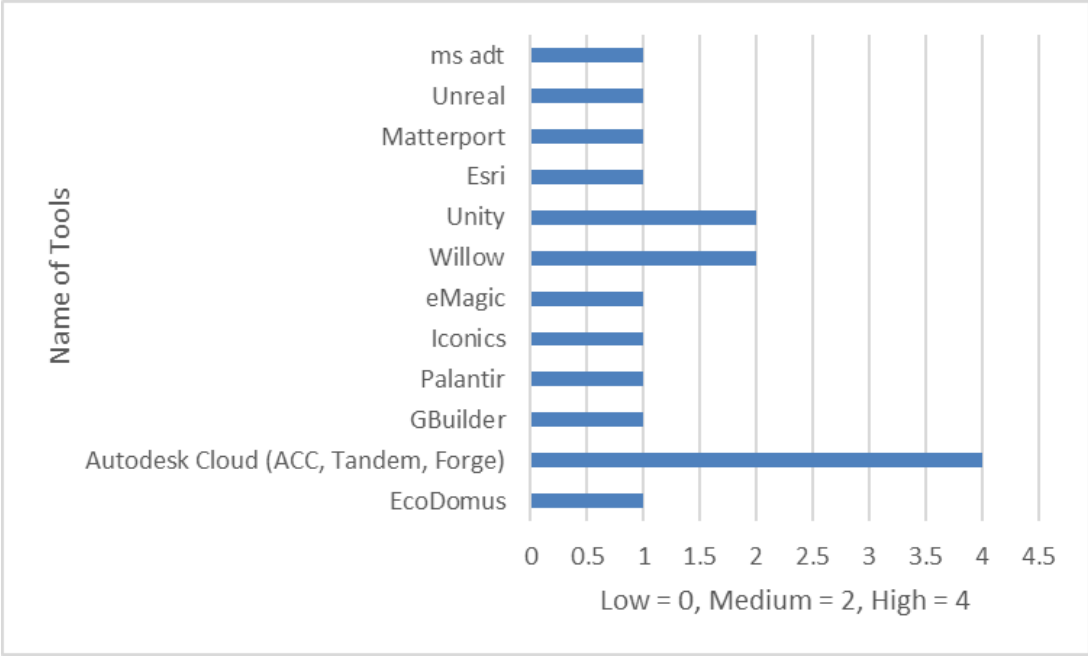


Figure 4:Tools used for DT implementation

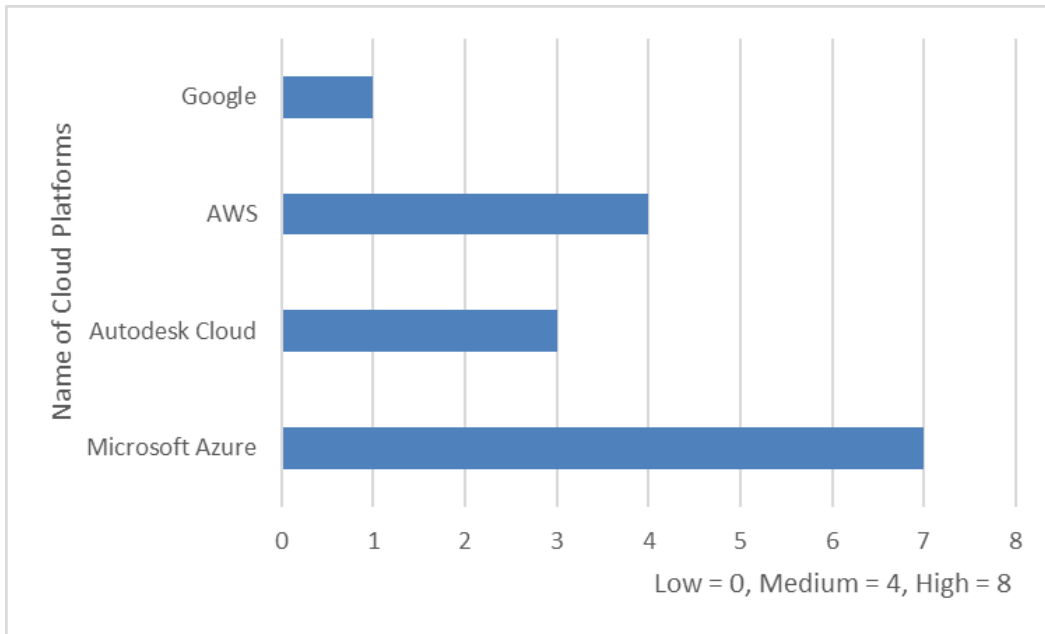


Figure 5: Cloud Platforms used for DT Implementation

During the interview, DT Developer 1 talked about the tools that can leverage the data in a better way as in the AECO industry we get a lot of data from different sources and manage these data as garbage in and garbage out with the end in mind and creating the data that will give us benefits in downstream. He gave an example that having a better BIM design process with Revit-like tools and having the right information from them can give us a larger picture of the project. Also, he thinks while creating these tools if the design community can collaborate with equipment manufacturers, then equipment can be built in a way that will already come with appropriate data. Then design community will have a lower lift to get the right data from the BIM model. Also, he added, it will benefit us to have the right data during operation and maintenance too. He emphasized that we are still trying to develop an appropriate tool for the Digital Twin system and while developing these tools we should focus on having the right information easily and user friendly.

DT Developer 2 also emphasizes that we should have a tool that can help us to weigh and adjust data points for getting into live Digital Twin sorting millions of data points and being able to automatically tag those points with their associated metadata system. He gave an example that an air handling unit with temperature sensors. He says, *“This air handling unit will be feeding air into a certain room in a certain building. We will be tagging this temperature with location and*

*then it will be fed by the electric panel. So, we can see the building is made up of a complex web of equipment that is both being fed by and feeding certain areas. And this equipment is in a certain area and is maintained by certain people. So being able to quickly have all these data and this relationship of data can be very beneficial for our industry. The ability to quickly, easily and accurately tag data within the twin system is the most important tool which is to some extent already out there and also needs to be developed. Namely, Revit, AutoCAD, Willow, Azure ADT, Sigma, etc, can be the tools for implementing the Digital Twin system.”*

DT Developer 3 says, *“We have been missing the VDC toolbox while thinking about the built environment. There has been strong delivery of BIM for design and engineering purposes and now BIM has also been used for general contracting and construction management as a part of VDC. But the real-estate operation and facility management has not been able to follow these processes and benefits from the digital representation of buildings because they are inheriting static data whereas they required a lot of live data. So Digital Twin is now coming to tie this loop. The Digital Twin is creating a system that enables the technical performance of the built environment along with having the live data.”* Also, she is hoping that the Digital Twin system will change the precatave facility management and maintenance to be more proactive so people start to fill in their data literacy in terms of what is the data indicates to them and when should they go and do maintenance because that's the most affordable way of keeping things running. She is hoping Digital Twin tools can be seen as a technology that can also help us in expense planning and then eventually create the opportunity for avoiding unnecessary investment and cost in the AECO industry.

DT User 1 is working on a bunch of projects through BIM 360, design, or Autodesk collaboration platform like using the Revit tool. Although they are a general contractor, they are also modeling in-house but still, there are a lot of subcontractors who do not necessarily use Revit, however, they will access the model through the collaboration cloud as it's a common data environment where they share models. She says, *“Revit as a tool is great for the design team but it's not great for construction and fabrication. So, we use that as a reference but not to fabricate letting our fabrication team use their own tool. We also use Naviswork for clash detection and for final coordination to make sure that there are no clashes that we have in the plan while we build it at work. Regarding the Digital Twin system, we as a general contractor deliver the product that*

*an owner's Digital Twin might need. We do not own the Digital Twin system and we do not feel the need to own it as we will hand over the project in two or three years. We provide the data in whatever format they ask us, but we do not feel the need to link these data unless we will be maintaining the twin in the long run because we are just handing over the product. So right now, it is just handing over assets and information in whichever format they ask us to.”* They leverage these data by doing terrestrial scanning, drone flights, 360 photo capture, scheduling, cost estimating, and progress tracking of the project.

DT User 2 explains that right now there is no specific name of the tool for the Digital Twin system as they have been evaluating tools from different vendors and trying to figure out the most efficient tool for the Digital Twin system. For them, tools like IoT, and visualization tools like AR/VR are certainly important tools. She says, *“Using a tool like AR/VR we can experience the space if we have a concrete raw space then we are using such tools to engage a potential tenant in the space so they can understand what that space could be. We use a tool called Matterport to create a virtual tour and overlay rendered images over that concrete raw space to make it feel more real. And tools like laser scanning can be used for existing spaces and develop models from those. Also having a tool for a robust Digital Twin system for tracking the data that are required for us.”*

Overall, there are lots of great tools that are available for implementing Digital Twin. These tools are capable of their task but still, we need to use multiple tools to achieve the complete Digital Twin. Also, a lot of these tools are very expensive and complicated to use which is also creating confusion among most organizations about whether they should use these tools or not. So, there is still a search going on for finding the best tool for implementing Digital Twin and until now none of the tools has created dominance in the industry. But it is found that people are also accepting the tools developed by the vendors that they are following from the beginning of modern tools like BIM.

### **4.3 Implementation Strategies of Digital Twin**

Digital Twin technology in the AECO industry is aimed to incorporate all the stakeholders involved in a project. They should be able to easily access the data they require by having a common data environment. It also requires organizational and inter-organizational collaborations

among all the stakeholders. Also, Digital Twin is aimed to implement from conceptual to whole life-cycle management of the project. In each phase of the project, each stakeholder will have a key role in implementing Digital Twin. Like when a project is started an owner plays the deciding role on whether to implement Digital Twin or not. Then in the conceptual phase architects and engineers play key roles in implementing Digital Twin. Also, it will be critical during data transfer from designers to contractors for the continuation of Digital Twin implementation. Then general contractors, project managers, and suppliers also play vital roles to align their project delivery workflows with the Digital Twin system. After completing the construction of a project, acquiring the data for operation and maintenance, and for asset or facility management, different stakeholders like the facility manager and even the end-users play an important role in implementing Digital Twin.

Along with the stakeholders like owners, designers, and contractors, their consultants or technology developers are also crucial for the efficient implementation of Digital Twin. The successful adoption of Digital Twin in an organization requires technical competencies along with organizational readiness. To achieve the technical competencies major stakeholders of built environments like owners, designers, and contractors should collaborate with Digital Twin developers. It requires activities like digitizing their works, having required technology and technical knowledge in the team, and maintaining the Digital Twin system architecture with workflows for technology implementation. Also, to achieve organizational readiness, training the staff for Digital Twin adoption and implementation process, having leadership support, and financial resources for technology purchase are required.

In addition, having a Digital Twin strategic plan to adopt and implement the technical and organizational aspects of Digital Twin is important. To have a broader and current picture of the organization's Digital Twin implementation strategy, the research team asked their survey respondents. The following figure gives us an overview of the organization's investment in Digital Twin technology.

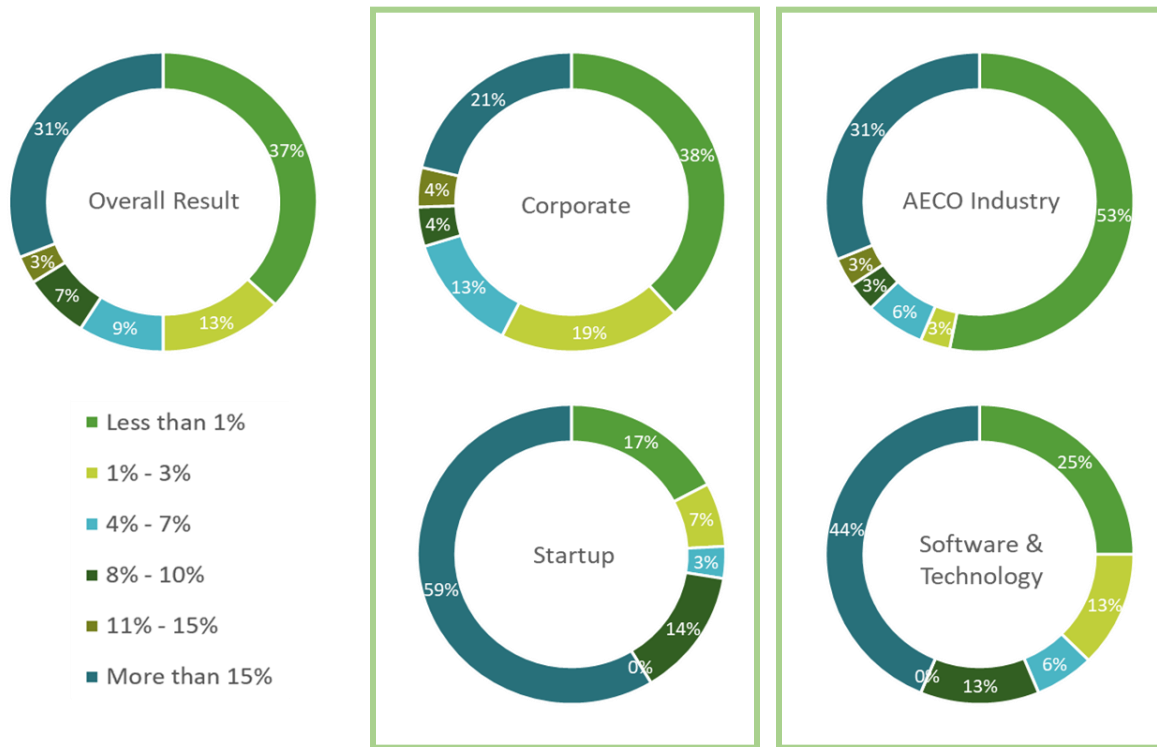


Figure 6: Average Percentage of Organization's Annual Revenue invested on DT Implementation

The overall result shows that currently, about one-third of the organizations (participated in the study) spend more than 15% of their annual revenue on Digital Twin adoption, while more than one-third spend less than 1%. For a more accurate analysis, the results were broken down for the AECO industry compared to the software & technology industry and then for corporates versus startups (as two types of DT developers). The fact that most of the startup companies in the Digital Twin market are specialized to provide Digital Twin products and services justifies the higher percentages of investment among startups compared to high-tech corporates (e.g. about 60% of startups invest more than 10% of their revenue compared to 30% of corporates). In the AECO industry, 53% of organizations spend less than 1% of their revenue on Digital Twin (compared to 25% in the software & technology) and 31% invest more than 15% of their revenue on Digital Twin (mostly including real-estate developers and large facility owners) while the number for the software & technology organizations is 44%.

Digital Twin implementation strategy should be in detail describing the steps of implementation both at a technical and organizational level. It is evident now that Digital Twin is the future of the AECO industry. So, the majority of industry personnel are trying to implement Digital Twin in their organization. But still, there is confusion about what exactly is Digital Twin

and what makes them Digital Twin users in their projects. To solve this confusion and to implement Digital Twin successfully, a Digital Twin implementation strategy is crucial. The implementation strategies can be prepared at a project or an organizational level. The project-level implementation strategy can be done in basic steps and by only choosing a certain portion of the project. This will help their staff to have an idea about how to implement Digital Twin in the project. Then gradually they can use Digital Twin to facilitate the whole project by having real-time data of physical objects in the digital world and using that data for monitoring and controlling the building system. Also, by preparing the strategy at the organizational level, Digital Twin can facilitate the multiple projects that the organization is carrying out and represents the portfolio of the organization’s projects with both static and dynamic data.

In terms of developing a Digital Twin strategy, 33% of the survey respondents (from the AECO industry) mentioned that they have a Digital Twin -related initiative while about 40% said they have a strategic plan (almost equally divided between Digital Twin strategy at the project level and organizational level). It should be noted that in this question, Digital Twin was used as a general term for Digital Twin process and practices and not necessarily referred to implementing a specific Digital Twin solution.

Table 3: The Survey Results related to the DT Strategy of Organizations in the Construction Industry

<b>Which of the following best describes your Digital Twin strategy?</b>	
We do not anticipate adopting DT within the next 5 years.	4.8%
We anticipate having a DT initiative within the next 5 years.	21.4%
We currently have a DT ad-hoc or pilot initiative	33.3%
We have a strategic plan for DT adoption and implementation.	19.0%
We have a DT strategic plan connected to our organizational planning and business intelligence.	21.4%
<b>What is your organization's strategy towards implementing and managing the Digital Twin?</b>	
Using in-house staff	35.3%
Outsourcing	11.8%

Hybrid (using both in-house staff and third-party consultants)	52.9%
<b>Which of the following best describes your organization's in-house capabilities required for Digital Twin adoption and implementation?</b>	
We do not currently have staff with the required capabilities.	5.6%
We have less than 5 staff with the required capabilities.	55.6%
We have more than 5 staff with the required capabilities.	33.3%
I do not know if we have staff with the required capabilities.	5.6%

In addition, more than half of the respondents reported that they use a hybrid approach (using both in-house staff and third-party consultants) for implementing Digital Twin while 33% of the organizations have more than 5 staff and 55% have less than 5 staff with the required capabilities.

During the interview, DT Developer 1 explained he has been developing a Digital Twin solution with the in-house staff in his organization. Also, they are providing professional services as a consultant to Digital Twin users/customers. The main aim of their consultation is to empower the owner with having their own in-house capability to manage the Digital Twin. But the problem is Digital Twin is a new technology for the AECO industry so most of them need to hire a consultant to implement Digital Twin. He says, *“If we think for a long period of time then, for implementing Digital Twin, having in-house staff would be more beneficial. For example, Denver Airport asked their contractors to develop the BIM models and after getting that model they managed it on their own. They have their in-house staff capable and ready to manage and update these models and use them for maintenance.”* As per him for implementing Digital Twin, around 25% of their total staff should have the knowledge of Digital Twin system. But he said that the data will be used by a larger group of people who may use some tools or mobile apps so they can leverage that by going out to the site. He added the other remaining staff can also use these data by using virtual reality or augmented reality and should be able to use these data by using these visualization tools or other software and apps.

DT Developer 2 in implementing strategies for Digital Twin emphasizes having a unified software platform rather than having to log in to different software that is not sharing the data. He said it will greatly decrease the time that takes to investigate simple building issues that they have in their project. For implementing Digital Twin, they do 95% of their work. They have a smart building team that works on different protocols, IP, both IT & OT systems, and cyber security which help us greatly in our Digital Twin implementation process. For other issues like geographical issues and so they hire a consultant to work. As per him for implementing Digital Twin, 20% of total staff should have intermediate knowledge and 40% of total staff should have general knowledge of the Digital Twin system. But he believes everything in the Digital Twin system is interlinked so people in other parts of the organization should also know a good amount about implementing Digital Twin.

DT Developer 3 says for implementing Digital Twin hiring a consultant would be easier as we can have the latest and greatest people dedicated to the Digital Twin system in our team rather than going through the continuous process of educating and training people. She says, *“It will be very expensive and if it’s not a personal passion of people then they might be reluctant to learn. Also, the AECO industry has a huge gap to cover in achieving a digital transformation. The AECO industry is still in the process of transforming from paper-based drawings to CAD-based drawings. People in the industry think they are digitizing by having a pdf, but pdfs cannot run computer algorithms to extract attributes, which will not change our outputs. So, for implementing Digital Twin we should actually digitize rather than just digitize by adopting the emerging tools without holding ourselves hostage to the 1900s technologies and processes. But the problem is these emerging tools are just going to increase costs for us as we are just adding these tools with no obvious evidence of delivering any change. It’s troublesome for us that we need to get comfortable being uncomfortable with technologies that we have no clue about and those who are accepting these technologies are also confused as there are so many technologies coming from every direction that it’s impossible to learn at all. But if we can get to the same baseline that we agree with having the 100% digital delivery then it can become more manageable or balanced and harmonized.”*

For implementing Digital Twin, Developer 3 thinks everyone in the organization should have knowledge about the Digital Twin that is just enough to be dangerous so they will green light

the use of Digital Twin rather than unplug it. She says, *“If we are a stakeholder then we become a gatekeeper of adopting new technologies in a project and due to the lack of our understanding, we will be blocking everybody else. This will break the process of implementation. So, it’s everyone’s responsibility to understand Digital Twin as like everyone’s responsibility to learn math or read or write.”* She also said that there are fundamental technologies that belong to everyone in the AECO industry like Cloud Platforms, extended reality, Artificial Intelligence, and Digital Twin is one as well. It is important for the built environment.

DT User 1 is using technology that can be leveraged in somebody else’s Digital Twin as they do not own or manage the Digital Twin system. They are using technology like terrestrial scanning, drone flights, 360 photo capture, 3D models, and so on. She thinks Digital Twin systems are more beneficial for facility management so owners having them makes perfect sense. Similarly, manufacturing having Digital Twin in-house makes perfect sense as it will be widely used for manufacturing equipment but in construction, it’s just a multi-trade installation and after completion, we need to hand over the building, so it does not necessarily make sense for a general contractor to own and operate the Digital Twin. She believes that the Digital Twin system will find its way to being implemented in the next 5 to 10 years and she as a general contractor will need to have more tools for delivering the requirements of the Digital Twin system.

DT User 2 emphasizes that Digital Twin systems need to have standards for successful implementation so that they can create consistency which will be maintained from the design phase all the way to construction and building turnover. They are currently working with only in-house staff but are planning to hire consultants to help them with the implementation process of the Digital Twin system. They are not planning to build their own platforms, so she thinks it is better to hire consultants to resolve resource issues like time and people. Also, she said that a couple of people in her organization may continue to work part-time for Digital Twin implementation for a number of years as they have some really great projects to start implementing Digital Twin, but they need to have standards in place to start. As a leading general contractor company, they need to go through the process for implementing Digital Twin and need to have a definite answer of what benefits they can get by implementing Digital Twin. She thinks 70% of the total staff needs to know about the Digital Twin system for successful implementation of Digital Twin. She says, *“Down the road if it becomes the client requirement then the operational team needs to know, the*

*leadership team needs to know, business development and marketing team need to know so they can communicate well. The only exception might be the accounting team and some other backhouse staff but still, the majority of staff need to understand what it is so we can be successful.”*

Also, to understand what phases of the project are commonly using the Digital Twin system the research team asked their respondents what the primary Digital Twin use cases in their organization are. By this question, research team tried to figure out what phases of the project are using the Digital Twin system at maximum and what are the minimum use cases. The research team separated the responses from the people who are working directly in the AECO industry from others so we can have a better idea of what phases of projects in the AECO industry are using the Digital Twin system.

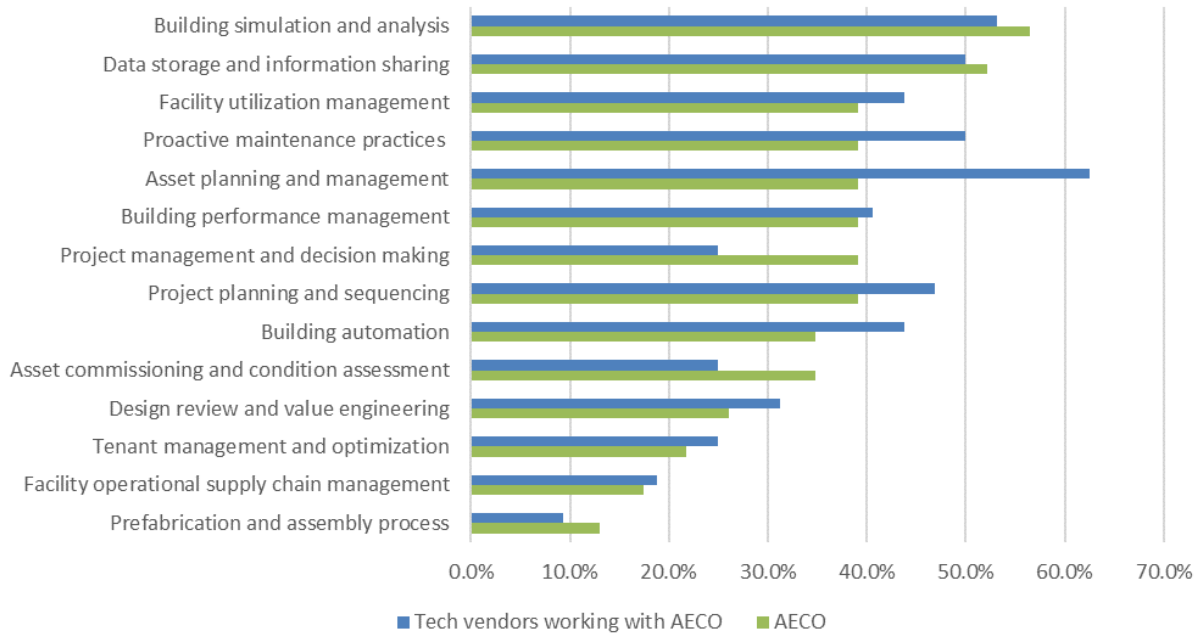


Figure 7: Primary used cases of DT

As from the figure above, for building simulation and analysis the AECO industry is mainly implementing Digital Twin technologies. Then mainly for data storage and information sharing, asset planning and management, proactive maintenance and practices, project planning, and sequencing we found that AECO is implementing Digital Twin technologies. This shows that AECO is implementing Digital Twin in the initial planning and designing phase of the project and then it is implementing it as a data storage and information sharing platform only.

In follow up to the responses that the research team got through the survey, I asked my interviewees what phases of the project they are using the Digital Twin system and why they are only using it in that phase.

DT Developer 1 explained that they are in the early phase of implementing Digital Twin. They are implementing it mostly in the planning and design phase as they have a Building Information Modeling tool that can implement Digital Twin systems. He said that the implementation is more in the planning and designing phase because most architects, engineers, and also the owners are using tools like Revit. As per him, almost 80% to 90% of designers and architects are using Revit whereas only 40% to 50% are only using Revit on the construction site. So, most people are still not using Revit in construction as well as operations and facility management. He says, *“We need to resolve this to have an efficient implementation of the Digital Twin system. For example, in a typical project, we will design the project and we have to take the as-built information and get that into the facility management tool like Maximo. Completing this whole process i.e., transferring the data from the design cycle to the maintenance cycle requires months of time. So, this data transformation process is creating a problem and if we have the Revit or similar tool which can be used in both cycles then it can save our time and make a smooth flow of data which will ultimately help in the implementation of the Digital Twin system.”*

DT Developer 2 said they have done implementation of the Digital Twin system in all - preconstruction, construction, operation, and maintenance phases. He says, *“Among all the phases implemented in preconstruction is easier as they can work with the contractor and collect documents in any format and digitize them. The most important thing for implementing Digital Twin is to communicate early and decide what a Digital Twin is supposed to do. Deciding which construction trades, we are using Digital Twin early can help us in gathering data from these trades.”* He believes the reason behind having gaps in implementing Digital Twin in the construction phase is as for most of the part construction industry is an industry that is very hard to change. He also said, *“It is difficult for us to show the people on the ground, what benefits they can have by implementing Digital Twin. But now we can observe some changes in construction too. For example, large construction companies are using big TV screens on the construction site where they can pull up digital drawings and make changes right there.”* He also added that the other reason for having difficulty in implementing Digital Twin is for many years construction

workers are working using paper drawings and making changes by using pen and paper, so we need to train our workers to use these modern types of equipment on-site too.

DT Developer 3 said they are mostly using Digital Twin in the operational phase as Digital Twin tools are operational, and management focused right now. She says, *“The Digital Twin system is a fairly new concept, so developers have not been able to catch up to commissioning Digital Twin-based projects. They are still figuring out the BIM-based project delivery and it's challenging to add a Digital Twin system right away. For adding the Digital Twin system, we need to have a good strategy for our implementation management and also for digital building lifecycle management. The most important thing for having this is while contracting we need to have a contract stating we are having BIM-based projects rather than drawing-based projects. So it's a fun challenge for a construction company and they individually need to start developing their digital contractor strategies and then start thinking about what does it mean for their digital building life cycle strategies and their information management strategy, their technology strategy, and project implementation strategies like how people collaborate across different departments they have because there's not much collaboration and integration happening as its still silent until today.”*

DT User 1 says it's possible to implement Digital Twin in any phase of the project but it's easier to implement in the preconstruction phase because as a general contractor it's easier for them to deliver the deliverables that an owner's Digital Twin requires in the preconstruction phase. She emphasizes that if we want to implement Digital Twin then it is crucial to have the scope of work that we need to perform. When they have twin requirements, they can work on budgeting and get some contractors or subcontractors on board who will understand these deliverables. She says, *“I think I am just a part of the data stream like I don't see the contractor owns Digital Twin, but I am just a piece of data that goes into it and in what format I should provide it at the end.”* She thinks for implementing Digital Twin in the construction phase owners need to take lead by defining those requirements in detail. Then all trades will follow it. To bring the change in construction we need to show the value that different trades will get by having Digital Twin. Then the second they can see the value they will go out and buy it and get the training and elevate themselves in the industry.

DT user 2 says *“I would be lying if I say we are using it fully now. So, I would say and in full transparency, we are really in the beginning stage of it. We have been talking about it for a long time, we have been doing and implementing it in a work order management system which is a very small piece of what will be Digital Twin but right now we are really focused on the very beginning stage.”* On the reason behind having gaps in implementing Digital Twin during the construction phase she thinks it’s because we are not great in handing off from design to construction and in certain dimensions as early as in the whole coordination process. She says, *“There is disconnection while shifting from one phase to another, like when we bring subs on board and what they are modeling, what the data they are getting, we are not sure about that. Also, there is a huge amount of time that goes before we get as-builts and final submittals which are important for operating the building. The close-up process takes so long time which creates a disconnection in data transfer to operation and maintenance too. So, in the long-run construction is missing so much data which also depends on the technical ability of the owner. Next, we as a general contractor need to educate the owner as a lot of them are going to ask for Digital Twin in the future. So, it’s important to teach the owners about the importance of consistency and standards and how we get from design all the way to construction. This will help us to have smooth data transfer from one phase to another phase of the project. Also, the next thing that is going to come soon is a model as a contract document as Nation BIM teams are working on it and maybe in the near future we can rely upon the model for consistency. But we may have to consider the fact that models can be changed during construction and must state we cannot rely on models when we are using them during design and construction. So, there are works that need to be done as a process and create some standards for implementing Digital Twin in all phases of a project.”*

It seems like a lot of organization in the construction industry has started to talk about implementing Digital Twin but still, they are not sure how they can implement it. Most of them are found to be unprepared and not ready to implement the Digital Twin. Although there is an interesting change in them from the technical ability as almost all of them have started to use BIM technology. This shows that now they are ready for complete digitization but that does not mean they are ready for Digital Twin. Also, through this research, we can conclude that there needs to be strategic planning at an organizational level for the successful implementation of the Digital Twin. They need to make their staff ready for the changes that they are going to have by providing training, software, and tools. Also, vendors and developers should make the software easier, and

user-friendly so general workers of our industry can also use it. We should try to make our in-house staff capable of using Digital Twin instead of hiring the consultants so in the long-run return on our investments will be higher.

#### **4.4 Benefits and Challenges of Digital Twin**

The benefits and challenges of implementing Digital Twin go hand in hand. Although it seems challenging to implement Digital Twin, it is also giving lots of benefits to the construction industry. But having a clear vision of challenges that we may face gives us a better idea to prepare strategies for implementing Digital Twin. Also knowing the benefits that we can have by implementing Digital Twin in our organization help us to convince our upper management and owners for implementing Digital Twin.

##### **4.4.1 Benefits and Opportunities of Digital Twin**

In this modern world keeping track of modern technology is always beneficial for everyone. Digital Twin is the future of the construction industry and being equipped with Digital Twin technology at the right time can make an organization a fortune. The present data and research show Digital Twin implementation can benefit different aspects of the organization which is also increasing the trend of adopting Digital Twin. One benefit an organization can have is cost-benefit which is a major aspect in construction or any other industry. Researchers have analyzed these benefits in different categories like project lifecycle (planning, design, construction, and operation), impacted stakeholders (contractors, facility managers, etc.), and organizational versus technical product/process benefits.

The implementation of Digital Twin can benefit us from conceptual to lifecycle management of a project. In the conceptual or planning phase, it provides an opportunity to access various data sources like past project information, organizational and environmental data, and city or state regulations. It also facilitates owners to express their requirements and speed up the design process. Also, in the preconstruction phase, Digital Twin provides an opportunity to carry out value engineering with simulation-based analysis. It enables us to modify the 3D model in the virtual world and analyze the feasibility of the structure and benchmark the expectation of the project performance.

Also, in the construction phase, Digital Twin provides us an opportunity to have live data on project progress helping us to control and monitor the project cost and schedule. It also enables the automation of project progress reporting, increasing the accuracy of data. At the same time, it will help us to analyze these live data in reference to the past records which is beneficial for planning the next task in the project. It also creates a better planning and coordinating environment for construction by having virtual model coordination, site logistics planning, etc., and reducing RFIs, rework and work delays. Digital Twin also provides opportunities for monitoring and detecting safety issues such as building structure failures or alarming safety risks by monitoring construction workers' activities. We can also track down the material or machinery and productivity at the job site by having a Digital Twin system. Also, during project closeout, Digital Twin helps us to prepare a punch list enhancing the process of commissioning and handover.

Also, in the operation and life cycle management phase, Digital Twin supports the maintenance activities and helps in facility and asset management. The automated and machine learning system of Digital Twin provides an opportunity for real-time monitoring and control. The data from different sensors fitted in the building/project makes us capable of service life tracking, condition assessment of building systems, fault detection, and diagnostics, and optimization of equipment performance and assets' quality. Digital Twin enables us to increase the efficiency of operation and maintenance systems reducing the long-term O&M cost. Also, for commercial buildings, Digital Twin facilitates space monitoring and management that optimizes tenants' experience and employees' productivity.

Along with these phase-based benefits, Digital Twin also provides organizational and technological benefits to the project. It can be a source of efficient communication among all the stakeholders involved. It enables a common data-sharing environment which improves collaboration and transparency in a project. It receives and analyzes the data from different sources and provides us with useful information which can be used for what-if scenario analysis, case-based reasoning, performance prediction, and prescriptive analytics. This integration helps different stakeholders to make informed decisions and prioritize sustainability throughout the project lifecycle management.

To better understand the extent of the identified benefits, the research team asked their survey participants to rank the main benefits (in a given list) of adopting and implementing Digital

Twin within their organizations or for their customers. The main Digital Twin benefits in the construction industry are shown in Figure 8.

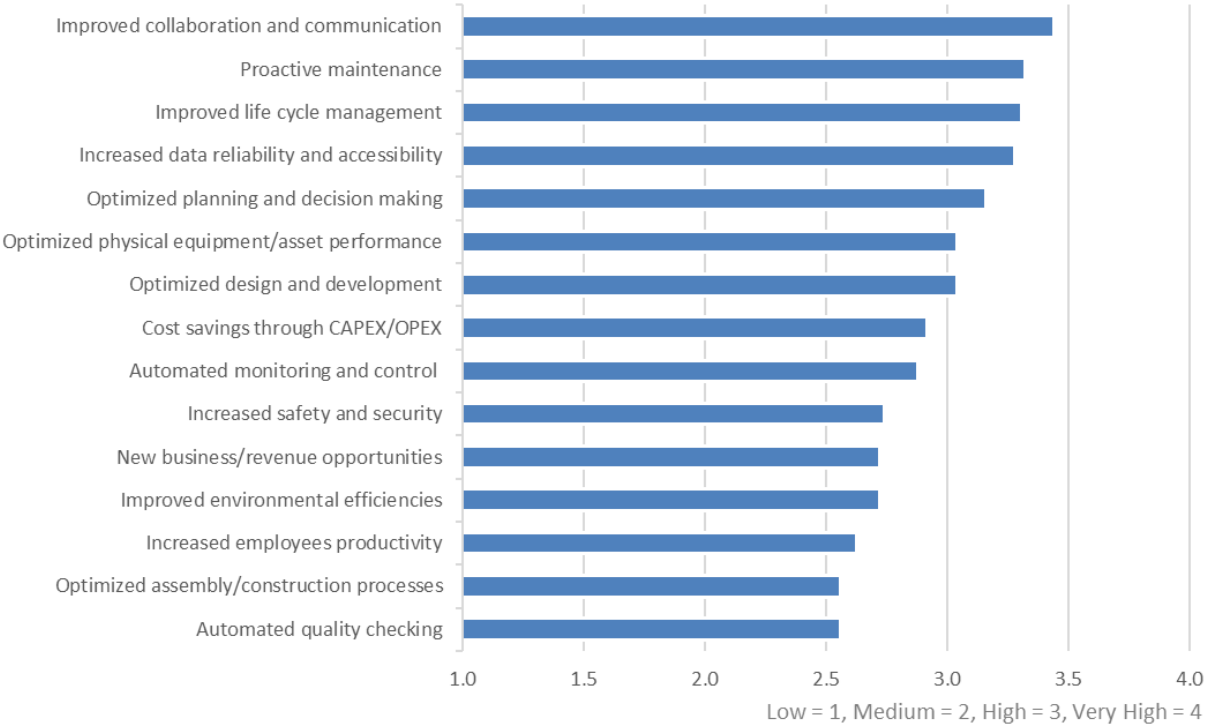


Figure 8: Main Benefits of DT Adoption in the AECO Industry

Based on the survey results, improved collaboration and communication is the primary beneficial outcome of Digital Twin adoption in the construction industry. It was followed by proactive maintenance, improved lifecycle management, and increased data reliability. This result confirms an emerging positive shift in the industry towards taking a lifecycle approach for adopting technologies and leveraging data with a focus on the operation phase of the project (which has been traditionally less considered compared to the design and construction phases). In addition, optimization of processes (planning and decision making) and products (physical assets) is the next key benefit reported by the respondents. Overall, all intended benefits are in a close range of importance (2.5-3.5, while 1 represents low and 4 represents a very high level of importance).

Additionally, Table 4 presents a more detailed summary of results by comparing responses in the three categories of the AECO industry, Digital Twin technology users (including other industry sectors such as manufacturing and energy/utilities), and DT technology developers. For

this table, besides ‘mean’, the ‘standard deviation’ was also calculated to better interpret the responses’ distributions. The scale is 1 to 4 from lower to higher.

Table 4: Benefits of DT Adoption and Implementation

Benefits	AECO Industry		DT Tech. Users		DT Tech. Developers	
	Mean	StDev	Mean	StDev	Mean	StDev
Automated monitoring and control	2.880	0.93	3.103	0.85	3.243	0.83
Automated quality checking	2.560	0.65	2.795	0.83	3.054	0.88
Cost savings through CAPEX/OPEX	2.917	0.97	2.974	0.81	3.111	0.89
Improved collaboration and communication	3.440	0.82	3.308	0.80	3.162	0.93
Improved environmental efficiencies	2.720	0.89	2.897	0.88	2.973	0.87
Improved life cycle management	3.304	0.82	3.410	0.68	3.108	0.91
Increased data reliability and accessibility	3.280	0.74	3.300	0.69	3.405	0.76
Increased employees’ productivity	2.625	1.17	2.846	1.01	2.694	1.04
Increased safety and security	2.739	0.96	2.921	0.85	3.027	0.96
New business/revenue opportunities	2.720	1.02	2.744	1.04	2.865	0.82
Optimized assembly/construction processes	2.560	0.82	2.846	0.87	2.838	0.99
Optimized design and development	3.040	0.89	3.000	0.92	2.889	0.89
Optimized physical equipment/asset performance	3.042	0.81	3.205	0.73	3.081	0.89
Optimized planning and decision making	3.160	0.75	3.237	0.71	3.243	0.80
Proactive maintenance	3.320	0.69	3.308	0.83	3.216	0.89

According to Table 4, all three categories of respondents selected the same items as their top five benefits although the orders were different (the DT tech. developers selected Automated

monitoring and control instead of Improved lifecycle management). The DT tech users reported Improved lifecycle management and the DT tech. developers reported Increased data reliability and accessibility as their most important benefits of adopting Digital Twin. Also, respondents' opinions (in all three categories) were relatively divided about the benefit's extent of Increased employees' productivity which may be due to the applicability of this benefit to different respondents. In other words, while this option is very applicable to manufacturing, and commercial building operations, it may not be much applicable to other Digital Twin market sectors. In addition, respondents in the DT tech users and AECO industry groups had divided opinions about how Digital Twin adoption helps organizations to develop new business/revenue opportunities. This may refer to the fact that different types of organizations exist in the Digital Twin market. Generally, startup companies can adopt new business paths quickly while corporates may need more time and coordination to incorporate Digital Twin -enabled business opportunities into their business plans and offering services.

After getting the results from a survey on the benefits of implementing Digital Twin in the AECO industry, I also asked my interviewees about what benefits they are having in their organization by implementing Digital Twin. I got the following responses from my interviewees.

DT Developer 1 believes that we can have cost benefits and savings over the construction and life cycle management of the building. Also, he emphasized that Digital Twin helps us in data management and to get the right data at the right time. It will help us to leverage and channel our data system in a systematic way like transferring all the data at the utmost level from the design cycle to the building lifecycle management. Also, developer 1 explained having the Digital Twin system will also help us in the visualization process. For example, if we have some issue in the plumbing system of our building then with the help of the Digital Twin system we can know where the problem is located and how can we access that and solve that. It will increase the efficiency of our work and reduce the chances of having to rework and any damages to other systems of the building.

Also, about the benefit of the DT Developer 1 says *“From a design firm perspective, this is a huge ability to gain more services instead of just being involved in a design process which can last just for a year or two and a construction process another two or three years. The ability to get into maintenance and operations and be involved in Digital Twin or maintenance of Digital Twin*

*can expand the life cycle of designers' work for years to decades. Not only for the designed project but if you are the owner of the Digital Twin then you will be invited back to do any retrofit work or changes in the building. So, the Digital Twin from a design firm perspective is an opportunity to elongate their work activities.”* So, we can see having the Digital Twin system allows Digital Twin owners to be involved in the project for the whole lifecycle of a project and that can be anyone like an owner, architect, contractor i.e., whoever owns the project. Also, the Digital Twin system will help to create a more collaborative environment among these stakeholders by increasing their involvement in the project and creating a common data environment.

DT Developer 2 also emphasizes data system management benefits which enable us to leverage the data to make informed decisions. He also explained how the Digital Twin system helps us in visualizing different issues during the operations and maintenance phase of the project. Also, he talked about how Digital Twin systems can bring automation to the construction industry for operation and maintenance activities. For example, by using different temperature sensors in different rooms, we can maintain the air handling units timely and avoid us from having any issues related to it.

DT Developer 3 says the main benefit of having a Digital Twin system is that we will have a complete digital representation of our assets which helps us to know the digital truth about the technical performance of our built environment. Also, she believes Digital Twin enables us to have proactive maintenance by shifting our mindsets from reactive facility management. She is also hoping that Digital Twin will help in expense planning avoiding unnecessary costs that incur in the project. She believes that Digital Twin is going to tie the loops and fill out the gaps that we have in the AECO industry. It will create data literacy among all the stakeholders and emphasizes the importance of data management for the efficient lifecycle management of the project.

DT User 1 believes the Digital Twin system creates a more collaborative environment by having a common data environment. She says she is already sharing the Revit models with their subs and if the Digital Twin system takes over the construction industry as planned then it can also bring other stakeholders like owners, architects, and engineers into a common data environment too. Also, if Digital Twin systems have the standard requirements for implementation, then she will have a better idea about what deliverables she should provide which help in solving lots of confusion that has been going on in the construction industry right now. Also, she believes it will

help those contractors who have to do extra work as the owner is asking for everything by not knowing what they really want.

DT User 2 said that Digital Twin systems are going to help us all in collaboration by having systematic data management. In the construction industry, we have a lot of data, and we are still trying to figure out how to manage all this data properly so we can benefit from all these data. She says *“Like you have a big building problem or big mechanical system problem, or plumbing problem then how do you start narrowing down so you have actionable data versus just like here is everything you possibly need or here is everything that possibly goes wrong or right. It ends up being deceitful for having what is most valuable and what can it tell us and what can I do with it, where should I focus. So, these can be solved by having a Digital Twin system.”* She also believes Digital Twin helps us in the visualization process and marketing the concrete raw space to the possible tenants by giving them a virtual tour of the space with overlapping rendered 3D images and showing what the space will look like.

Hence the most important benefit that the Digital Twin provides us is to manage our data. The construction industry has a lot of data and improper management of all this data are creating trouble to have a proactive action. Also, as the Digital Twin is going to create a common data environment it will increase the interaction and collaboration among all the stakeholders of the industry. It will also speed up our decision-making process and help us in planning better by providing an insight into the problem in advance. This will also help us to avoid unnecessary investments saving our cost and time.

#### **4.4.2 Challenges of Digital Twin**

Although we have lots of benefits from implementing Digital Twin, it's equally challenging for us to implement it in the construction industry. One of the major challenges that we have is related to data. This is because the construction industry is still in the process of digitization. People in the industry have recently realized the importance of digitization of the built environment for the life cycle and facilities management. So, the digitization process has been started but they are not sure what type of data is required and in what formats the data should be. This uncertainty about data is making it more challenging for implementing Digital Twin. The

table below provides a description of challenges related to data for the implementation of the Digital Twin system.

Tables 5: Data-related Challenges of DT Adoption

<b>Challenge with</b>	<b>Description</b>	<b>Reference</b>
Data availability, Data acquisition	It is challenging for organizations to determine their DT's lifecycle data requirements and acquire all required data based on it. Also, there are technical challenges with acquiring static/dynamic data (e.g. data abstraction and scalability).	[Lu et al. 2019, Errandonea et al. 2020]
Data quality	Inaccurate data and low-quality databases make it difficult to leverage data analytics and insights capabilities of a DT solution.	[Lu et al. 2019, Errandonea et al. 2020]]
Data accessibility, Data democratization	It may be difficult to provide all end-users inside and outside an organization with real-time access to reliable data and manage multi levels of access authorizations.	[Brink et al. 2020, Rasheed et al. 2020]
Data granularity, Data fidelity	It is difficult to balance between data-richness in the importing databases based on the end-users needs and preventing data overload in the DT system.	[Brink et al. 2020, Lu et al. 2020]
Data governance, Data management	Lack of standard protocols may cause challenges for utilizing DT-required common data environments to store, federate, and manage data received from heterogeneous sources.	[Lu et al. 2019, Brink et al. 2020, Rasheed et al. 2020]
Data interoperability, Data exchange	The challenge may refer to technical issues with data exchange between multiple digital systems as well as inconsistency between taxonomies of different databases.	[Turner e al. 2020, Fischer et al. 2020]
Data security	There are concerns about cyber-security attacks and lack of proper security measures to protect data since a DT solution entails extensive cloud-based dataflows between IoT, CDE and other systems.	[Rasheed et al. 2020]

Data ownership, Data confidentiality	A DT solution contains various databases, and it is unclear what stakeholder owns the data regarding intellectual property laws. Sharing data can also be challenging when it includes confidential data or causes conflict of interests.	[Madni et al. 2019, Jones et al. 2020]
Legacy data	It is usually challenging to transfer an organization's legacy data (with different data types, attributes, and schemas) from an old system to the newly adopted DT system.	[Brink et al. 2020, Rasheed et al. 2020]

After data challenges, we are also facing challenges with questions like how we should implement it. It's because there are no standards for implementing Digital Twin. For example, there are no standard and common formats of data in the construction industry for implementing Digital Twin. We are still in the process to find the best way to implement the Digital Twin system. They are using different tools and techniques available in the market. But a lot of these tools are not affordable to all stakeholders of the construction industry and not only a single tool will make it possible to implement the Digital Twin. So, there is no certain tool to standardize the implementation process of Digital Twin. The uncertainty in both the process and processes for implementing Digital Twin is also one of the key challenges of implementing Digital Twin.

At an organizational level, Digital Twin implementation seems challenging as the initial investment cost is higher for them, and they are not certain whether they will have a return on their investment or not. Also, if they want to have a Digital Twin system in their organization then they require full-scale digitalization of all the activities they perform through their organization. This required the increased technical ability of all staff of the organization which is challenging cause some of the staff of the organization may not be ready to cope with these changes. Having the organization's readiness/preparedness for accepting Digital Twin is also the most challenging aspect of implementing Digital Twin. Another challenge we have in organizations is their data safety. When implementing the Digital Twin system, we will be digitizing both the physical asset and intellectual assets of an organization. This may increase the risk of getting their private information public, risking the identity of an organization. So, organizations may face the challenge of privacy protection and the creation of protocols to ensure proper use of the collected

data in the Digital Twin system. Hence it will be challenging to create a unified digital platform which is the main concept of Digital Twin.

Although there are a lot of challenges, through this research the research team tried to know the most important one that we are facing in the industry. For that purpose, in the survey study, the research team asked participants to rank the main challenges (in a given list) for adopting and implementing Digital Twin within their organizations or for their customers. The main challenges in the AECO industry are shown in Figure 9.

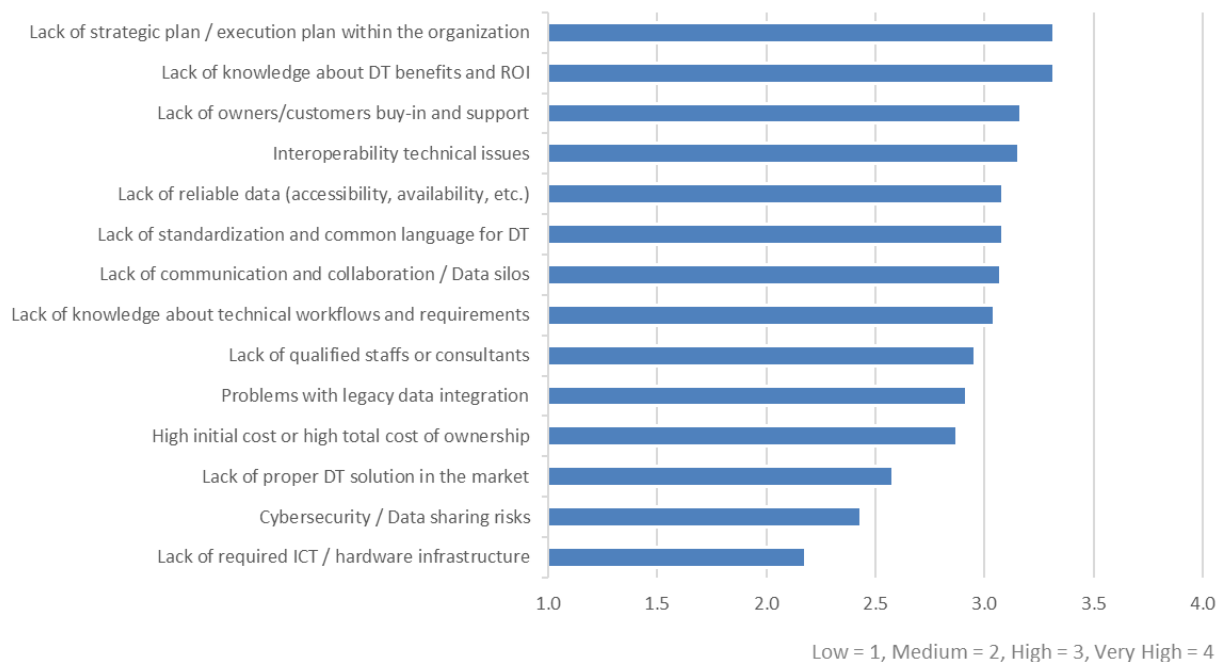


Figure 9: Main Challenges of DT Adoption in the AECO Industry

Accordingly, most of the identified challenges were rated as medium to high in terms of importance and severity. Lack of strategic/execution planning within organizations is the most important challenge for Digital Twin adoption in the current construction industry. Also, lack of knowledge about Digital Twin benefits and ROI as well as lack of owners' buy-in and support (which is related to the previous challenge) are the next important challenges. However, high initial cost/total cost of ownership is much lower in this ranking which reveals that the construction industry is willing to invest in this technology provided that more evidence is available about the feasibility and values of Digital Twin. A group of technical challenges including issues with data interoperability and reliability and lack of technical workflows are in the middle of the challenges'

ranking. On the other hand, technology availability and ICT infrastructure are not critical obstacles to Digital Twin adoption. In general, it seems the industry is following the same pattern as observed in the adoption of previous generations of digital technologies such as BIM. However, this result suggests that the industry is more mature in terms of recognizing the importance of data as well as standardization of workflows/planning in adopting and implementing new technologies.

Additionally, Table 6 presents a more detailed summary of results by comparing responses in the three categories of AECO industry, DT technology users, and DT technology developers. The scale for the Table 6 is 1 to 4 from lower to higher.

Table 6: Challenges of DT Adoption and Implementation

Challenges	AECO Industry		DT Tech. Users		DT Tech. Developers	
	Mean	StDev	Mean	StDev	Mean	StDev
Cybersecurity / Data sharing risks	2.435	0.99	2.579	0.92	2.361	0.87
High initial cost or high total cost of ownership	2.875	0.99	2.718	0.89	2.943	0.94
Interoperability technical issues	3.160	0.85	2.974	0.78	3.000	1.01
Lack of communication and collaboration / Data silos	3.077	0.84	3.179	0.82	2.946	0.81
Lack of knowledge about DT benefits and ROI	3.320	0.75	3.128	0.89	3.222	0.90
Lack of knowledge about technical workflows and requirements	3.043	0.77	2.949	0.89	3.029	0.86
Lack of owners/customers buy-in and support	3.167	0.76	3.077	0.77	2.857	0.97
Lack of proper DT solution in the market	2.583	0.97	2.590	0.88	2.600	1.09
Lack of qualified staffs or consultants	2.957	0.77	2.722	0.78	2.886	0.99
Lack of reliable data (accessibility, availability, etc.)	3.087	0.90	2.868	0.93	2.686	1.02
Lack of required ICT / hardware infrastructure	2.182	0.59	2.154	0.67	2.176	0.87
Lack of standardization and common language for DT	3.083	0.83	2.923	0.96	2.829	1.10
Lack of strategic plan / execution plan within the organization	3.320	0.90	3.050	0.96	2.800	0.96
Problems with legacy data integration	2.920	0.86	2.821	1.00	2.556	0.97

Table 6 indicates a general consistency between the responses of the three categories. As a difference, respondents from the AECO industry emphasized the lack of reliable data as a critical challenge while it was not among the top five challenges pointed out by respondents in the DT tech. users' category. Instead, they selected a lack of effective communication and collaboration as the most important challenge. Also, respondents' opinions were more divided in the DT tech. developers (compared to the other two categories) especially about the topics of standardization and common language for Digital Twin as well as the existence of proper Digital Twin solutions in the market.

Then I also did follow up with my interviewees about the challenges they are facing while implementing Digital Twin in their organization. The following are their responses of them:

DT Developer 1 talked about the idea of data cleanliness and hygiene and making sure that people are using the same and correct data and data standards. He says *“We worked with a number of owners, architects, and contractors and we asked them to think about the end state they are looking for and required designers and contractors to put the information in. But every customer/DT user wants to do it in a different way which is a problem. So, if every design firm uses a different standard and every owner uses a different standard then it's going to be impossible to share the information to have different projects done by different design firms and contractors. So, it really needs somebody to come in and level the whole field and say this is the data standards that we are going to work with. At present, IFC and building Smart groups are trying to come up with some data standards but the reality is that until everybody is speaking the same language it is going to be a problem. To have the solution to this, some people are saying that it is never going to happen or not possible to make all people use the same data standards, but we can use technology like semantic learning databases that bring these data together in a way. So now we readily admit that we have the technology to help us. So, this is a major challenge and if we had that today and everybody is speaking the same language then we could have been much more forward in implementing Digital Twin than as we are today.”*

DT Developer 2 on challenges of implementing Digital Twin says *“The biggest challenge is the change management within the customer and themselves as oftentimes they are trying to figure out whom the Digital Twin for. So, they are not quite sure whether this is a tool for facility management level or Building management level or is it for the building owner or building*

*operator or asset manager or CTO level. So not quite sure for whom Digital Twin is for and how to work with Digital Twins. So, we are trying to help customers to understand where they see themselves by implementing Digital Twin in order to encourage adoption. Next is probably working with the data that goes through the Digital Twin. Nowadays each party wants to have data run through their platform or their software or they want to be the platform that runs everything else through them. So, a lot of back-and-forth questioning on implementation is going on things like who is going to take data or copying the data or who is going to store all that data.”*

*DT Developer 3 on challenges on implementing Digital Twin says “Contractual challenges are one of them so depending on who the owner of the data is, who the owner of the building is that we are creating Digital Twin from. It might be either very easy or challenging or in some cases even difficult or impossible to get the live data linked to Digital Twin. So contractually that is the pinpoint generally needed to be considered with the industry. But otherwise, there are still interoperability issues with the industry because a lot of the systems that need to be plugged into DT are legacy systems, so they are not the latest system, and they are at the end of their technical lifecycle. So, the data collection might be unpromised and not be something that is linked to the cloud. So, there is a mixed system we need to be dealing with while plugging in data to Digital Twin. And also, there are trans-operability issues since Digital Twin is an emerging technology, and a lot of the building systems and automation and control systems, suppliers, and manufacturers they haven’t supported the indiscretion with their competitors. So, that’s an added complexity to everything but that’s an opportunity for the industry in order for everyone to survive their needs for transparency and collaboration rather than bloody competition. So, to wrap it, it’s an opportunity before the built environment industry to really embrace the platform economy building.”*

*DT User 1 emphasizes that it’s still challenging to define the scope of work required for implementing Digital Twin. She says, “We want to deliver information, I want a Digital Twin, so what does that mean? You have to develop a scope of work. What is that you need? Especially in construction what does Subcontractors X have to deliver? What is that each individual has to deliver? What is the architect/structure engineer needs to deliver? It has to be defined and unfortunately as Digital Twin is going to be owned by the building owner, they need to know what their focus is because there are a lot of ways you can take it and you can define what is it that you*

*need so you won't be wasting your money. Otherwise, you might not get the information you need. You cannot define it then I am going to hand over my deliverable so once they know what they want it needs to be defined in a format that not only I can bid but I can also execute. It has to be now in a contract somewhere. You write it down and say this is what it is. I think a specification is a great place to start."*

DT User 2 on challenges for implementing Digital Twin says it's challenging to create consistency among different stakeholders of the industry. She says, *"A lot of people perceive Digital Twin like, oh we build models for construction, we build them from 3D coordination then why cannot we use those models and these standards for implementing Digital Twin. We know because the way the process works the design team develops their model then there is a federated model that has some contractors involved in it then to get us to the end product is a hot fuzz of those things with all different standards and cooperative and I am thinking like naming conventions of equipment, spaces, floors, and things like that. I think these things can be done easily, maybe if an owner supports it. But that has to be consistent for us to be successful, so it is not just like pushing a button and I also think the biggest challenge is the data and how clean and concise it is. That's a problem that every organization is facing currently but how do we think about that on a building side as well."*

Hence, we came across a lot of challenges in implementing Digital Twin in the construction industry throughout this research. Most of the challenges are related to the lack of knowledge of an organization about the actual application of Digital Twin for them. As they are still confused about the concept of the Digital Twin, they are unable to make any strategic plan or develop any standards for implementing Digital Twin. Then they also have inconsistency in data collection which challenges them in creating a sound and secure data system. Also, our industry has just begun its transformation to digitization, so it still has interoperability issues for the efficient application of the Digital Twin systems. The requirements of advanced technical knowledge and investments in modern software and technologies with no certainty of ROI are also making it more challenging for instant implementation of the Digital Twin in the construction industry.

## **Chapter 5: Discussion and Conclusion**

### **5.1 Discussion and Conclusion**

During the research, I came into different aspects of Digital Twin Technology in the AECO industry. The first and foremost thing that makes me question is that a lot of people in the AECO industry do not know what a Digital Twin technology is. One of my interviewees, DT user 1 said most industry personnel have not even heard the term Digital Twin. They will be like digital what? So, there is still confusion in the definition of the Digital Twin. Even when I asked some of my colleagues in the university, they also told me this concept is new to them. So, the concept of the Digital Twin is new to both scholars and professionals in the construction industry. Through this research, I found that people in our industry are still incorporating Building Information Modeling (BIM) technologies. They are still trying to understand how BIM technology works and still making themselves ready for the digitization of the construction industry. Also, those who understand the term Digital Twin are also not sure what the actual definition of the Digital Twin is. They have their own understanding of Digital Twin as per the technology they are using in their organization. Like some will say they are using BIM, so they have a Digital Twin, or some say they have AR/VR technologies for visualization, so they have a Digital Twin. So, there is ongoing confusion in the definition of the Digital Twin in the construction industry.

The term Digital Twin is coined by John Vickers as having a twin or digital replica of a physical object. But the Digital Twin concept is not only based on that. To make a complete Digital Twin we required three major components: a physical object, its twin or digital replica, and the linkage and connection between them. It seems the majority of people are understanding Digital Twins with only two components i.e., physical objects and their digital replicas, and neglecting the most important component i.e., the connection between them. Also, up to now, the construction industry has been able to have these two components easily but linking them seems to be troublesome. They have not yet found a standard way to link these physical and Digital Twins. It is becoming more complex as the construction industry has a lot of data and they are not sure how to manage all of this data. Right now, they have just shifted from analog systems of data to digital systems and these digital systems are also created by using different tools with different formats of data. So now it is more challenging to link all these data to create a complete Digital Twin system.

The Digital Twin for the construction industry is aimed to be a system that will standardize all the data that we have in our industry and make them unified and provide us with useful information that we need and make them available to all the end-users by having a common data environment. It is aimed to fill in the gaps that we have in our data stream and make us a more proactive industry by enabling us to make informed decisions on time. The Digital Twin for the construction industry will have the data from the conceptual to the construction to the operation and lifecycle management of the project. So, people in the construction industry need to understand that a Digital Twin is more about the data than having a digital replica. Also, it's not about having the advanced software or tools, it's about how we manage and maintain our data system so we can have the right information at the right time.

The construction industry has always been trying to manage the data that they have in their own way. These data may be managed by using some legacy system or some modern system, but our goal is to bring them together into a unified system. With an aim to create a unified system, the construction industry is using different tools to have these data in the same format. The first and foremost step they are focused on is digitizing these data which may be done by laser scanning, machine learning through security cameras, BIM software, sensors, and so on. By this step we acquire our data into our digital system then we analyze them and visualize them to get useful information. The tools like IoT, Artificial Intelligence, and machine learning are used for data analytics and then different AR/VR software and BIM software are used to visualize this data. Through this research, we find out there is no standard tool for implementing Digital Twins. The tools like Tandem, Willow, and Unity have been widely used with an aim to achieve Digital Twin solutions. Also, the Digital Twin concept is based on making the data accessible to everyone and creating a common data environment. So, tools for cloud platforms are also essential for Digital Twin systems and cloud platforms like Autodesk cloud, Microsoft Azure, Google, and AWS are commonly used in the construction industry.

The next interesting thing that I found during this research is how our industry is planning to implement the Digital Twin system. As the concept of Digital Twin is entirely new to most of us, they said hiring an expert or consultant for implementing Digital Twin would be best for their organization. It is always a better option to call out the expert for the job but in the long run, our staff also needs to know about the Digital Twin system. It is because the Digital Twin system is

going to last the whole lifecycle of the project and having in-house staff capable of running the Digital Twin system will be beneficial for an organization. Also, most general contractors think it's not necessary for them to own a Digital Twin system as they will only be delivering and handing over the projects. They think that if they can provide the deliverables required for the Digital Twin system then that's enough. But as a concept of Digital Twin, there should be no ownership in the Digital Twin system. It should be a web of data systems that link data from one stakeholder to others and ultimately creates a common data system.

But creating a system without ownership is one of the most challenging things in the construction industry. It will question us about our data privacy. The construction industry is composed of different stakeholders and each of these stakeholders has its own roles and motives. Then to have a system without ownership we need to find the common motive for aligning these stakeholders which is one of the most complex things to do. Also, these stakeholders may not feel comfortable sharing all the data they have. This will contradict our main concept of Digital Twin to have a common data environment. Also, the initial cost to achieve a Digital Twin system is higher which is also pushing different stakeholders of our organization backward in implementing Digital Twin. In any industry, we expect to have a return on our investment, and yet there is no certainty about whether we will get the expected return by implementing Digital Twin or not. As there are not enough used cases to convenience the majority of the industry, it is still hard for us to see the full-scale implementation of the Digital Twin system.

However, it is interesting to see how progressively our industry is changing. Although our industry is very hard to change and still using the same ways for more than a century to get the job done. We are now seeing some positive changes too. The adoption of Building Information Modeling technologies has opened the door to digitizing our industry, opening more doors for other opportunities. Like, it has now opened the door for automation which is also increasing the value of modern technologies like the Digital Twin in our industry. Also, we are seeing a shift in leadership too. The millennials equipped with modern technologies are taking over the baby boomers and revolutionizing our industry. This shift in leadership with technical ability is also changing the technicality of our industry. To smoothen this shift and give a safe flight to the organization that wants to continue its journey in our industry, adopting Digital Twin can be helpful.

The main benefit that the Digital Twin system can provide is it can unify the fragmented structure of our industry. By implementing Digital Twin, we can have a more collaborative environment among different stakeholders of our industry. It can create a centralized system through which each party is connected and can communicate in need along with real-time data sharing. This will increase productivity along with speeding up the decision-making process. Also having the right data at the right time and enabling us to visualize those data and find out the area or place where we have the issue and recommend us the possible solution can save us a lot of time and cost.

## **5.2 Future Studies**

During this research, some interesting things came to light. Like, is a model required for the Digital Twin? Of course, the Digital Twin is more about data than having some model and we can acquire and visualize data in other formats too. But the main concept of the Digital Twin emphasizes visualizing the physical object in the digital world by having a digital “twin” replica. So not having a model or Digital Twin element in the Digital Twin system may be controversial to us but it makes us wonder in the future about what’s the importance of models. Also, a lot of technologies are coming into the market saying they can implement Digital Twin in our project. But we cannot acquire the required information without logging in and out to multiple systems. Also, this software is not that easy to learn. So, are these systems or software making it easier to do our work or is it just making it more complex? Don't we want to have Digital Twin to make our job easier? I think we need to think more about these questions in the future.

## **Bibliography**

Angjeliu, G., Coronelli, D., & Cardani, G. (2020). Development of the simulation model for Digital Twin applications in historical masonry buildings: The integration between numerical and experimental reality. *Computers & Structures*, 238, 106282.

Austin, M., P. Delgoshaei, M. Coelho, and M. Heidarinejad. 2020. "Architecting Smart City Digital Twins: Combined Semantic Model and Machine Learning Approach." *Journal of Management in Engineering* 36(4):04020026. doi: 10.1061/(ASCE)ME.1943-5479.0000774.

Ariyachandra, M. R. M. F., & Brilakis, I. (2020). Detection of railway masts in airborne LiDAR data. *Journal of Construction Engineering and Management*, 146(9), 04020105.

Barima, O. (2017) 'Leveraging the blockchain technology to improve construction value delivery: the opportunities, benefits and challenges', in Hall, K. (ed.) *Construction Projects*. New York, NY, USA: Nova Science Publishers, Inc, pp. 93–112. ISBN: 978-1-53610-742-5

Barykin, S. Y., A. A. Bochkarev, O. V. Kalinina, and V. K. Yadykin. 2020. "Concept for a Supply Chain Digital Twin." *International Journal of Mathematical, Engineering and Management Sciences* 5(6):1498–1515. doi: 10.33889/IJMEMS.2020.5.6.111.

Bock, T. and Linner, T. (2015), *Robot-Oriented Design. Design and Management Tools for the Deployment of Automation and Robotics in Construction*, Cambridge University Press, The Cambridge Handbooks in Construction Robotics.

Boje, Calin, Annie Guerriero, Sylvain Kubicki, and Yacine Rezgui. 2020. "Towards a Semantic Construction Digital Twin: Directions for Future Research." *Automation in Construction* 114:103179. doi: 10.1016/j.autcon.2020.103179.

Bolton A, Enzer M, Schooling J et al. 2018. "The Gemini Principles: Guiding values for the national Digital Twin and information management framework", Centre for Digital Built Britain and Digital Framework Task Group

Bosch-Sijtsema, Petra, Christina Claeson-Jonsson, Mikael Johansson, and Mattias Roupe. "The Hype Factor of Digital Technologies in AEC." *Construction Innovation* ahead-of-print, no. ahead-of-print (February 24, 2021). <https://doi.org/10.1108/CI-01-2020-0002>.

Boschert, Stefan, Christoph Heinrich, and R. Rosen. 2018. "Next Generation Digital Twin."

Brilakis, I., Y. Pan, A. Borrmann, H. Mayer, et. al. 2019. "Built Environment Digital Twinning". Siemens, Technical University of Munich ([https://publications.cms.bgu.tum.de/reports/2020\\_Brilakis\\_BuiltEnvDT.pdf](https://publications.cms.bgu.tum.de/reports/2020_Brilakis_BuiltEnvDT.pdf))

Cao, D., Li, H., Wang, G., Luo, X., Yang, X., Tan, D. (2016). "Dynamics of project-based collaborative networks for BIM implementation: Analysis based on stochastic actor-oriented models." *Journal of Management in Engineering*, 33(3), 04016055, [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000503](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000503).

Farghaly, K., Abanda, F. H., Vidalakis, C., Wood, G. (2018). "Taxonomy for BIM and Asset Management Semantic Interoperability." *Journal of Management in Engineering*, 34(4), [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000610](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000610).

Ford, David N., and Charles M. Wolf. 2020. "Smart Cities with Digital Twin Systems for Disaster Management." *Journal of Management in Engineering* 36(4):04020027. doi: 10.1061/(ASCE)ME.1943-5479.0000779.

Gartner. (2019). Top 10 Strategic Technology Trends for 2019. Gartner, (March 2019), 12. <https://www.gartner.com/doc/3891569?refval=&pcp=mpe>

Giel, B., Issa, R. R. (2015). "Framework for evaluating the BIM competencies of facility owners." *Journal of Management in Engineering*, 32(1), 04015024, [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000378](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000378).

Glaessgen, E. and Stargel, D. (2012). "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles." In 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, American Institute of Aeronautics and Astronautics.

Grieves, M. and Vickers, J. 2017. "Digital Twin: mitigating unpredictable, undesirable emergent behavior in complex systems." *Transdisciplinary Perspective on Complex System*, 85–113.

Jones, D., C. Snider, A. Nassehi, J. Yon, and B. Hicks. 2020. "Characterising the Digital Twin: A Systematic Literature Review." *CIRP Journal of Manufacturing Science and Technology* 29:36–52. doi: 10.1016/j.cirpj.2020.02.002.

Kaewunruen, S., & Lian, Q. (2019). Digital twin aided sustainability-based lifecycle management for railway turnout systems. *Journal of Cleaner Production*, 228, 1537-1551.

Kan, C, and C J Anumba. "Digital Twins as the Next Phase of Cyber-Physical Systems in Construction." *Computing in Civil Engineering*, 2019, 9.

Kwon, K. S., Rahman, M. K., Phung, T. H., Hoath, S. D., Jeong, S., & Kim, J. S. (2020). Review of digital printing technologies for electronic materials. *Flexible and Printed Electronics*, 5(4), 043003.

Lee, Dongmin, Sang Hyun Lee, Neda Masoud, M.S. Krishnan, and Victor C. Li. "Integrated Digital Twin and Blockchain Framework to Support Accountable Information Sharing in Construction Projects." *Automation in Construction* 127 (July 2021): 103688. <https://doi.org/10.1016/j.autcon.2021.103688>.

Lim, Kendrik Yan Hong, Pai Zheng, and Chun-Hsien Chen. "A State-of-the-Art Survey of Digital Twin: Techniques, Engineering Product Lifecycle Management and Business Innovation Perspectives." *Journal of Intelligent Manufacturing*, August 1, 2020. <https://doi.org/10.1007/s10845-019-01512-w>.

Lin, K., Xu, Y. L., Lu, X., Guan, Z., & Li, J. (2021). Digital twin-based collapse fragility assessment of a long-span cable-stayed bridge under strong earthquakes. *Automation in Construction*, 123, 103547.

Liu, M., Fang, S., Dong, H., & Xu, C. (2021). Review of Digital Twin about concepts, technologies, and industrial applications. *Journal of Manufacturing Systems*, 58, 346-361.

Love, P. E., & Matthews, J. (2019). The 'how' of benefits management for digital technology: From engineering to asset management. *Automation in Construction*, 107, 102930.

Lu, Ruodan, and Ioannis Brilakis. "Digital Twinning of Existing Reinforced Concrete Bridges from Labelled Point Clusters." *Automation in Construction* 105 (September 2019): 102837. <https://doi.org/10.1016/j.autcon.2019.102837>.

Lu, Q., Xie, X., Parlikad, A. K., & Schooling, J. M. (2020). Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation in Construction*, 118, 103277.

Lu, Qiuchen, Ajith Kumar Parlikad, Philip Woodall, Gishan Don Ranasinghe, Xiang Xie, Zhenglin Liang, Eirini Konstantinou, James Heaton, and Jennifer Schooling. “Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus.” *Journal of Management in Engineering* 36, no. 3 (May 2020): 05020004. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000763](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000763).

Ma, X., Xiong, F., Olawumi, T. O., Dong, N., and Chan, A.P., (2018). “Conceptual Framework and Roadmap Approach for Integrating BIM into Lifecycle Project Management.” *Journal of Management in Engineering*, 34(6), 05018011. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000647](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000647).

O’Dwyer, E., Pan, I., Charlesworth, R., Butler, S., & Shah, N. (2020). Integration of an energy management tool and Digital Twin for coordination and control of multi-vector smart energy systems. *Sustainable Cities and Society*, 62, 102412.

Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, and Maria Rashidi. “Digital Twin Application in the Construction Industry: A Literature Review.” *Journal of Building Engineering* 40 (August 2021): 102726. <https://doi.org/10.1016/j.jobe.2021.102726>.

Ozturk, Gozde Basak. “Digital Twin Research in the AECO-FM Industry.” *Journal of Building Engineering* 40 (August 2021): 102730. <https://doi.org/10.1016/j.jobe.2021.102730>.

Pan, Y., & Zhang, L. (2021). A BIM-data mining integrated Digital Twin framework for advanced project management. *Automation in Construction*, 124, 103564.

Pan, Z., Shi, J., & Jiang, L. (2020). A Novel HDF-Based Data Compression and Integration Approach to Support BIM-GIS Practical Applications. *Advances in Civil Engineering*, 2020.

Parris, Colin. “What Is a Digital Twin? | GE Digital.” (<https://www.ge.com/digital/blog/what-digital-twin>, accessed 12/30/20).

Peng, Y., Zhang, M., Yu, F., Xu, J., & Gao, S. (2020). Digital twin hospital buildings: an exemplary case study through continuous lifecycle integration. *Advances in Civil Engineering*, 2020.

Research, G. V. (2018). *Digital Twin Market Size, Share & Trends Analysis Report By End Use. Market Research Report*.

Rosen, R., Wichert, G., Lo, G., and Bettenhausen, D. (2015). "About the importance of autonomy and Digital Twins for the future of manufacturing." *IFAC-PapersOnLine*, 48(3), 567–572.

Salling, K. B., & Leleur, S. (2015). Accounting for the inaccuracies in demand forecasts and construction cost estimations in transport project evaluation. *Transport Policy*, 38, 8-18.

Sepasgozar, S. M. (2020). Digital twin and web-based virtual gaming technologies for online education: A case of construction management and engineering. *Applied Sciences*, 10(13), 4678.

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., and Wang, L. (2010). "Modeling, simulation, information technology & processing roadmap." *Technology Area 11*.

Shim, C. S., Dang, N. S., Lon, S., & Jeon, C. H. (2019). Development of a bridge maintenance system for prestressed concrete bridges using 3D Digital Twin model. *Structure and Infrastructure Engineering*, 15(10), 1319-1332.

Shirowzhan, S., Tan, W., & Sepasgozar, S. M. (2020). Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities. *ISPRS International Journal of Geo-Information*, 9(4), 240.

Siemens. "Digital Twin". (<https://www.plm.automation.siemens.com/global/en/our-story/glossary/digital-twin/24465>, accessed 11/15/21)

Son, H., Kim, C., and Kwon Cho, Y. (2017). "Automated schedule updates using as-built data and a 4D building information model." *Journal of Management in Engineering*, 33(4), 04017012. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000528](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000528).

Song, J., Migliaccio, G. C., Wang, G., Lu, H. (2017). "Exploring the influence of system quality, information quality, and external service on BIM user satisfaction." *Journal of Management in Engineering*, 33(6), 04017036, [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000549](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000549).

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., and Sui, F. 2018. "Digital twin-driven product design, manufacturing and service with big data." *The International Journal of Advanced Manufacturing Technology*, 94(9–12), 3563–3576.

Taylor, J. E., and Bernstein, P.G., (2009). “Paradigm trajectories of building information modeling practice in project networks.” *Journal of Management in Engineering*, 25(2), 69-76. [https://doi.org/10.1061/\(ASCE\)0742-597X\(2009\)25:2\(69\)](https://doi.org/10.1061/(ASCE)0742-597X(2009)25:2(69)).

Tuegel, E. J., Ingraffea, A. R., Eason, T. G., and Spottswood, S. M. 2011. “Reengineering Aircraft Structural Life Prediction Using a Digital Twin”

Valero, E., Adán, A., & Cerrada, C. (2012). Automatic method for building indoor boundary models from dense point clouds collected by laser scanners. *Sensors*, 12(12), 16099-16115.

Vick, S., & Brilakis, I. (2018). Road design layer detection in point cloud data for construction progress monitoring. *Journal of computing in civil engineering*, 32(5), 04018029.

Wang, Q., Guo, J., & Kim, M. K. (2019). An application-oriented scan-to-BIM framework. *Remote sensing*, 11(3), 365.

Yitmen, I. (2021). *BIM-enabled cognitive computing for smart built environment: Potential, requirements, and implementation*. CRC Press.

Yu, G., Zhang, S., Hu, M., & Wang, Y. K. (2020). Prediction of highway tunnel pavement performance based on Digital Twin and multiple time series stacking. *Advances in Civil Engineering*, 2020.

Zhao, L., Zhang, H., Wang, Q., & Wang, H. (2021). Digital-Twin-Based evaluation of nearly zero-energy building for existing buildings based on scan-to-bim. *Advances in Civil Engineering*, 2021.

Zhang, J., Zi, L., Hou, Y., Wang, M., Jiang, W., & Deng, D. (2020). A Deep Learning-Based Approach to Enable Action Recognition for Construction Equipment. *Advances in Civil Engineering*, 2020.

Zheng, Xiaochen, Jinzhi Lu, and Dimitris Kiritsis. 2021. “The Emergence of Cognitive Digital Twin: Vision, Challenges and Opportunities.” *International Journal of Production Research* 0(0):1–23. doi: 10.1080/00207543.2021.2014591.